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Fractures in Rock
An Annotated Bibliography

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January 1990

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ETL

90 03

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
January 1990

3. REPORT TYPE AND DATES COVERED
Bibliography: June 1986-September 1989

4. TITLE AND SUBTITLE
Fractures in Rock: An Annotated Bibliography

5. FUNDING NUMBERS
4A161102B52C,OC, 010

6. AUTHOR(S)
Judy Ehlen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Topographic Laboratories
Fort Belvoir, Virginia 22060-5546

8. PERFORMING ORGANIZATION REPORT NUMBER
ETL-0555

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This bibliography lists many papers concerned with fractures. Subjects addressed include: descriptive and quantitative characteristics of fractures, mechanisms of fracture initiation and propagation, methods for obtaining information on fractures in the field, and procedures for analyzing and interpreting the data in the laboratory. Papers on engineering applications are also included. Each entry is annotated and key words are given.

14. SUBJECT TERMS
Bibliography, fractures, data analysis, engineering, rock mechanics, geology, joint propagation

15. NUMBER OF PAGES
44

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Preface

Part of this bibliography was compiled under DA Project 4A161102B52C, Task OC, Work Unit 010, "Indicators of Terrain Conditions."

The bibliography was prepared between June 1986, and September 1989, partly under the supervision of Dr. J.N. Rinker, Team Leader, Center for Remote Sensing; and of Dr. Richard Gomez, Director, Research Institute.

Col. David F. Maune, EN, was Commander and Director, and Mr. Walter E. Boge was Technical Director of the U.S. Army Engineer Topographic Laboratories during preparation of the report.

Fractures in Rock: An Annotated Bibliography

Introduction

Analysis and interpretation of rock fracture patterns provides an important contribution to many types of civil works and military projects. Examples include the siting of major engineering works, such as dams, tunnels, and nuclear and toxic waste repositories, and the prediction of potential ground water locations and subsurface routes of comtamination.

The papers in this bibliography are associated with the study and measurement of fracture characteristics in outcrop, primarily joint spacing and orientation, remote sensing of same, and the subsequent analysis of those data. Because the study of fractures in rock spans so many disciplines, no bibliography can be comprehensive and this one is thus only a partial bibliography. Three types of papers are included: 1) papers based on field work, 2) papers based on experimental work, and 3) papers that are theoretical in nature. The summary of each paper is prefaced by keywords that refer to the geographic area where the work was done, the rock type, the subjects addressed and, in some cases, the type of paper, e.g. experimental or theoretical. Footnotes cite papers referred to in the annotations that are not included in this bibliography.

Most of the papers based on field studies of fractures address sedimentary rocks and usually deal with fracture orientation. These include papers by Pincus (1951), Hobbs (1911), Ehlen (1976) and Holst and Foote (1981). Among the papers that deal with joint spacing in sedimentary rocks are Parker (1942), Harris et al. (1960), Rats (1962), Mastella (1972), McQuillan (1973), Wheeler and Stubbs (1979), Ladeira and Price (1981), Verbeek and Grout (1984) and Narr and Suppe (1988). Joint spacing in igneous rock outcrops was investigated by Ehlen and Zen (1986). Bourke et al. (1981), Bourke et al. (1982) and Thorpe (1979) studied fracture orientation and spacing in igneous rocks using cores and in drill holes. Seeburger and Zoback (1982) studied the subsurface characteristics of fractures in both igneous and sedimentary rocks. Methods of collecting data on fractures in the field are dealt with in a number of studies. Robertson (1970), Call et al. (1978), ISRM (1978) and Hencher (1987), for instance, discuss methods of field measurement. The use of remote sensing techniques is investigated by Blanchet (1957), Brown (1961), Boyer and McQueen (1964), Gay (1972), Ehlen (1976), Grillot and Razack (1985), Bevan and Hancock (1986) and Mohammad (1987). In addition, data analysis procedures are addressed by Pincus (1951), Hudson and Priest (1979), Thorpe (1979) and Wheeler and Stubbs (1979).

There is also a large body of literature concerned with the origin and propagation of joints. These include excellent review papers by Kranz (1983), Atkinson and Meredith (1987), Engelder (1987) and Pollard and Aydin (1988). Other theoretical papers include those by Secor (1965), Hudson and Priest (1979), Segall (1984), Segall and Pollard (1983a, 1983b) and Olson and Pollard (1988, 1989). Experimental work is described by Peng and Johnson (1972), Hoagland et al. (1973), Knapp and Knight (1977), Swain and Hagan (1978), Nemet-Nasser et al. (1978) and Nemat-Nasser and Horii (1982). Nur and Simmons (1970), Simmons and Richter (1976), Kobayashi and Fourney (1978) and Kranz (1979) have done experimental work concerned specifically with microcracks.

Allen, J.E. 1987. "Joints in rock provide clues on lava flow," *The Oregonian* (Portland, OR), 1 January, pp. B1 and B3.

Keywords: columnar joints, basalt, classification

The purpose of the article is to develop a classification for joints in lava flows. The origin of lava flow joints (cooling) is discussed and a descriptive classification based on ranges of block or column size is proposed. Sketches of the proposed types are included, as are color photographs of some of them.

Atkinson, B.K. and Meredith, P.G. 1987. The theory of subcritical crack growth with applications to minerals and rocks. In *Fracture Mechanics of Rocks*, edited by B.K. Atkinson. London: Academic Press, pp. 111-166.

Keywords: fracture mechanics, theory, experimental work

Traditional fracture mechanics are inapplicable under conditions of long-term loading, particularly if high temperatures or a reactive environment are present, i.e. in the area of subcritical crack growth. Much of the experimental work discussed in this paper was done using glass and ceramics because so little work has been done with rocks.

The micromechanics of fracture are briefly discussed with respect to fractures controlled by pre-existing cracks, by cracks generated through microplasticity, by general plasticity/grain boundary sliding, by cleavage and intergranular fracture and by intergranular creep.

Suggested mechanisms for subcritical crack growth are: stress corrosion, dissolution, diffusion, ion-exchange and microplasticity. The concept of stress corrosion is that chemical reaction strains bonds, allowing the weakened bonds to be broken more easily at lower stresses. As crack velocity decreases, cracking becomes mainly intergranular. Diffusion may be the main mechanism for cracking in ceramics at high temperature. Crack paths are irregular and occur mainly where there is a lot of intergranular cavitation. Dissolution could well be important if the dissolution rate is fast enough. With respect to ion-exchange, growth at high velocities is controlled by the chemical composition of new crack surfaces, and at low velocities, by the chemistry of the external environment. Microplasticity is effective in the damage or process zone and is favored by high temperatures and low strain rates. Work with quartz indicates there is no plastic behavior at crack tips up to 250 degrees. Constitutive modelling of subcritical crack growth is discussed in terms of lattice-trapping theories, thermodynamics, reaction rate theories and process or damage zone theories. Reaction rate theories give good descriptions of subcritical crack growth. Chemically-assisted fracture is material specific, but should be very widespread. Lawn's (1975)[1] two-stage theory, that reactive species must be transported to the site before crack-facilitating reactions can occur, is apparently the best. Later workers amplified Lawn's work to show that propagation is in fact identical to chemical reaction. This theory refers to the microscopic or submicroscopic level; process zone theories refer to macrocracking. Macrocracking appears to depend on the development of sufficient damage at the crack tip. Work in this area is only semi-quantitative and it is not as yet related theoretically to work at the microscopic scale. All studies of subcritical crack growth assume linear elastic behavior, but it is likely this may not be the case.

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[1] Lawn, B.R. 1975. Atomistic model of kinetic crack growth in brittle solids. Journal of Materials Science, vol. 10, pp. 469-480; and Lawn, B.R. and Wilshaw, T.R. 1975. Fracture of Brittle Solids. Cambridge, England: Cambridge University Press, 204 p.

Experimental data on rocks and minerals is summarized. Only mode I cracks have been studied. In quartz, subcritical crack growth is thermally activated. Fluid pressure and pH are also important. Quartz sandstones, granites, basic igneous rocks, marbles and limestones are discussed. Experimental results are not reproducible and are very limited. Generally, increase of temperature in environmental water increases crack velocity at constant stress. This data is extrapolated to the crustal environment with respect to stress intensity, temperature, activity of reactive chemical species, influences on microstructure and residual strains, and growth limit and healing. Cracking is separated into three regions with respect to stress and velocity. In region 1, velocity is controlled by stress corrosion; in region 2, by the rate of transport of reactive species; and in region 3, by thermally-activated processes. All factors are important in all regions, however. With reference to microstructure, it appears that ceramics become more resistant to fracture up to a certain grain size and then the trend reverses. Suggestions/ requirements for further work are also given.

Aydin, A. and DeGraff, J.M. 1988. Evolution of polygonal fracture patterns in lava flows. *Science*, vol. 239, pp. 471-476.

Keywords: columnar joints, basalt, propagation, Idaho, Hawaii

Joint surface morphology and joint intersection geometry were used to study the formation and evolution of columnar joints in Idaho and Hawaii. Joint growth occurs incrementally, producing segments. T-type intersections occur on the edges of flows, and Y-type intersections are found in the interior. These produce tetragonal and hexagonal columns, respectively. Evolution occurs from T-type to Y-type intersections and the segments are produced sequentially. The change is gradual.

Babcock, E.A. 1973. Regional jointing in Southern Alberta. *Canadian Journal of Earth Science*, vol. 10, pp. 1769-1781.

Keywords: Canada, joint orientations, regional patterns, sedimentary rocks

This paper discusses "...the geometry of joint patterns and the relationships between joints and regional structure and stratigraphy on the southern Alberta plains" (p. 1769). Up to 150 joint orientations were measured or, if there were less than 150, all joints were measured. The actual number of measurements needed for analysis was not determined; however, the author found that 80 measurements are not enough. Most measurements were in nearly horizontal sandstones and siltstones. Rose diagrams were used to display the data. Linear and circular statistics were compared; there were virtually no differences between the two procedures. Systematic joints occur in sets; they are normal to bedding and cross other joints. Nonsystematic joints are random in pattern; truncated joints occur normal to and between systematic joints. Surface detail, such as plumose structure, is rare. Ranges are given for joint spacing: sandstone, 15 cm to 1 m; shale, 0.5-20 cm; and coal, 1-10 cm. Two orthogonal systems that occur throughout the area were identified; a third system that is more local may also exist. No regional variation in joint pattern could be attributed to differences in lithology or statigraphic position. The results are compared to the work of others in this and other areas. The joints are considered extension fractures, but because they cannot be dated, only possible origins are suggested.

Barton, C.C., Samuel, J.K. and Page, W.R. 1988. Fractal scaling of fracture networks, trace lengths, and apertures. *Geological Society of America Abstracts with Program*, vol. 20, pp. A299.

Keywords: fracture networks, fractals, sedimentary rocks, Nevada

The use of fractals in predicting fracture network patterns at depth at Yucca Mountain, Nevada, is investigated. Soil and vegetation were stripped from bedrock pavements and the fracture networks were mapped. Published maps of fracture networks were also evaluated. The fracture networks are fractal at all scales (over six orders of magnitude in Nevada). Trace length and aperture are also fractal in nature.

Bevan, T.G. and Hancock, P.L. 1986. A late Cenozoic regional mesofracture system in southern England and northern France. *Journal of the Geological Society of London*, vol. 143, pp. 355-362.

Keywords: France, England, stress analysis, remote sensing, sedimentary rocks

The purpose of the paper is "...to describe and interpret a regional system of late Cenozoic mesofractures that cut Upper Cretaceous and Paleogene rocks in S England and N France" (p. 355). The pattern trends northwest and results from contractions on pre-existing faults. The sedimentary rocks are flat-lying. Fracture orientation does not change with rock type. Vertical extension joints are most common. Fracture spacing increases and planarity and size decrease from east to west, i.e. toward southwest England. Lineation analyses were also done using Landsat imagery. The northeast-trending set of lineations prominent in France is not prominent in England.

Bisdom, E.B.A. 1967a. The role of micro-crack systems in the spheroidal weathering of an intrusive granite in Galicia (NW Spain). *Geologie en Mijnbouw*, vol. 46, pp. 333-340.

Keywords: Spain, granite, weathering, microcracks, flaking

Pressure release is generally accepted as the cause of large-scale sheeting and dome formation, but its relation to scaling and flaking is unknown. Chapman and Greenfield (1949)[2] suggested dilation due to hydrolysis, oxidation and carbonation, and Schattner (1961)[3] suggested decreasing strength away from cooling centers. The granite, a coarse-grained, biotite-hornblende granite, was separated into zones ranging from unweathered rock with only structural microcracks to weathered material with released scales. Structural microcracks in zone 1 can be distinguished from weathering microcracks in zones 2 and 3 by the absence of iron oxide, their straightness and their angular intersections. Microcracks occur in two ways: 1) directed toward the core and 2) parallel to the outer surface. The scales themselves are filled with sinuous microcracks arranged as overlapping discoids. Boulders becomes concentric because weathering is most intense on corners. The following distinction in terminology is proposed: "Spheroidal weathering thus applies to the arrangement of scales and flakes around the boulder, and concentric banding to the crack system involved" (p. 357). Concentric banding

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2 Chapman, R.W. and Greenfield, M.A. 1949. Spheroidal weathering of igneous rocks. American Journal of Science, vol. 247, pp. 407-429.

3 Schattner, I. 1961. Weathering phenomena in the crystalline of the Sinai in the light of current notions. Bulletin of the Research Council of Israel, vol. 10 G, pp. 247-266.

disappears toward the center of a disintegrated boulder because the cracks within the scales continue to enlarge. These results are supported by neither Schattner's theory nor pressure release theories (on this scale).

Blanchet, P.H. 1957. Development of fracture analysis as exploration method. *American Association of Petroleum Geologists Bulletin*, vol. 41, pp. 1748-1759.

Keywords: remote sensing, fracture analysis, Canada

The paper begins with a series of definitions. Fracture is defined as an air photo lineament, for instance, and systematic joints are thought to be caused by earth tides resulting from fatigue. Blanchet believes the fractures are generated about halfway down the sedimentary column and propagate upwards. The steps that comprise fracture analysis are listed using an example.

Bloom, A. L. 1978. Pressure release on unloading: Sheeting. In *Geomorphology: A systematic analysis of Late Cenozoic landforms*, edited by A. L. Bloom. Englewood Cliffs, NJ: Prentice-Hall, pp. 106-108.

Keywords: sheeting joints, joint spacing, landform, stress release

This is a subsection of a chapter. Sheeting joints result from rock expansion in the upper few kilometers of crust due to removal of "overburden," i.e. unloading. Sheeting only occurs in very massive rocks; in other types, joints or bedding "absorb" the expansion. Joint spacing increases with depth (specific examples are given). Most believe sheeting results from "...diminution of primary confining pressure by removal of superincumbent load..." (p. 107), but some support the idea of "...local or regional compressional stresses (tectonic)" (p. 107). Sheeting develops near the surface because of low geothermal gradients and virtually constant temperature. Propagation occurs along pre-existing microcracks. Massive rocks tend to have low geothermal gradients, which, added to the absence of other "imperfections" to take up stress, explains why sheeting is so common in them. Dome size is controlled by other joints, but shape is controlled by sheeting.

Bourke, P.J., Bromley, A., Rae, J. and Sincock, K. 1981. A multi-packer technique for investigating resistance to flow through fractured rocks and illustrative results. In *Siting of radioactive waste repositories in geological formations*, Proceedings of the Nuclear Energy Agency Workshop (Paris). Paris: Organization for Economic Co-operation and Development, pp. 173-187.

Keywords: subsurface data, granite, S.W. England, joint spacing, nuclear waste disposal

If radionuclides leak from their repositories, the most likely way they will be transported is through fractures by water. Rates of flow and pressure gradients through fractures thus need to be determined so that rates and times of radionuclide flow can be predicted. Information on pressure gradients and resistance to flow were published previously; this paper addresses the problem of whether or not flow occurs through a few large fractures or many small ones. A multi-packer system is used in a 200 m deep, 100 mm wide bore hole, between depths of 100 and 200 m, in S.W. England in the Carnmenellis granite. Observation of pressure data indicated that the fracture system at depth is connected to the surface and is filled with water below the water table. Flow is laminar. Flow enters the hole from 12 short, widely-spaced zones of high hydraulic conductivity. This suggests 12 discrete fractures or 12 thin layers of highly permeable rock. Seven zones of fractures and dykes were also identified (I assume from core), but there is no statistical correlation between flow zones and fracture zones. The average separation between fractures is about ten meters.

Bourke, P.J., Evans, G.V., Hodgkinson, D.P. and Ivanovich, M. 1982. An approach to prediction of water flow and radionuclide transport through fractured rock. In *Geophysical investigations in connection with geological disposal of radioactive waste*, Proceedings of a Nuclear Energy Agency Workshop (Ottawa, Canada). Paris: Organization for Economic Co-operation and Development, pp. 189-198.

Keywords: subsurface data, granite, S.W. England, joint spacing, nuclear waste disposal

In this paper, an attempt is made to apply percolation theory using tracers to the identification of individual fractures. Bourke et al. found that radionuclide movement may be severely retarded with respect to water movement, depending on the thickness of rock between fractures (i.e. joint spacing). Five 10-centimeter wide, 200-meter deep vertical holes spaced 2-25 m apart and one hole at 45 degrees to the vertical were drilled. The authors began with single hole tests to identify and locate fractures and then "inserted" the tracers. The tracers showed the fractures to be interconnected in most cases. The data for one hole show fewer fractures between depths of 50-100 m than between depths of 100-200 m and also show mean spacing increases upward in that hole.

Boyer, R.E. and McQueen, J.E. 1964. Comparison of mapped rock fractures and airphoto linear features. *Photogrammetric Engineering*, vol. 30, pp. 630-635.

Keywords: remote sensing, Texas

The study compares linear features identified on the ground to those identified on air photos to test correlation between them. Field work and photo analysis were done independently (the photos were about 1:16,000 scale). Each ground-identified linear feature was represented by at least one lineation on the air photos. Major rock types in the area are granite, carbonates and some sandstone. Rose diagrams show the orientation distributions. Joint sets and air photo linears compare very favorably, particularly for granite.

Brown, C.W. 1961. Comparison of joints, faults, and airphoto linears. *American Association of Petroleum Geologists Bulletin*, vol. 45, pp. 1888-1892.

Keywords: remote sensing, Texas

Some air photo linears may well be fractures, but others may not, so the purpose of the paper is to emphasize the need for caution in interpretation. Joint spacing was recorded in the field, but was not consistent regionally or locally, so the data are not presented in the paper. The results of field work and air photo analysis were compared using histograms. An average of 66% of the sets coincided, but the author does not believes this suggests a genetic relationship. The correlation between faults and air photo linears is very good, however.

Brunner, F.K. and Scheidegger, A.E. 1973. Exfoliation (abstract). *Rock Mechanics*, vol. 5, pp. 43-62.

Keywords: sheeting joints, theory, joint spacing

Exfoliation (sheet jointing) is usually pre-glacial and is independent of primary structures. "Plate thickness" increases with depth (i.e. joint spacing becomes wider with depth) and ordered orientation is lost at about 50 m. The stress relief theory is shown to be unsuitable. They present a model of fracture by induced tensional stress, which explains the parallelism of these fractures with the surface, the increase in spacing with depth and their disappearance at depth.

Call, R.D., Savely, J.P. and Nicholas, D.E. 1976. Estimation of joint set characteristics from surface mapping data. *Proceedings of the 17th U.S. Symposium on Rock Mechanics, Salt Lake City, Utah*, pp. 2 B2-1 to 2 B2-9.

Keywords: joint spacing, slope stability, methodology, engineering

The purpose of the paper is to define a method for predicting the probability of slope failure using fracture characteristics. The joint set characteristics evaluated are length, spacing, waviness, orientation and overlap. Sampling is discussed and the authors cite other work indicating that 100 observations per joint set is ideal; they, however, say that there is little change in mean spacing after 30 measurements. Three mapping methods are discussed: detailed line survey, the recurrence interval method and fracture set mapping. The latter two can only be used if joint sets can be identified at the outcrop and if the outcrop is of sufficient size. The authors emphasize the detail line survey. Joint characteristics are defined. Statistical methods are not recommended for identifying joint sets because they are too rigid and too few variables can be included. The authors prefer using Schmidt net plots and engineering judgement. The distributions for the variables are determined and this data is fed into stability equations; Monte Carlo sampling is then used. Only dip is normally distributed; other variables have negative exponential distributions.

Chapman, C.A. 1958. Control of jointing by topography. *Journal of Geology*, vol. 66, pp. 552-558.

Keywords: Maine, topography, joint control, sheeting joints, granite

Joint patterns and distribution in Acadia National Park are largely controlled by surface conditions. The rock is a coarse, massive hornblende granite. Vertical joints and sheeting joints are both more abundant on hilltops and higher slopes than on the glaciated valley sides, and joints are less common on broad, rounded hilltops than on narrow, sharp ones. There are generally two to three sets of well-formed joints in addition to one to three sets of poorly-developed joints. The dominant joints are those favorably oriented to lateral expansion directions. The sliding downslope of sheeting layers releases pressure and allows joints parallel and perpendicular to the direction of movement to open. Joints are truncated by sheeting, indicating they opened after sheeting occurred and are thus surficial features. Joints tend to turn and parallel cliff faces. Sheeting and topography allow favorably-oriented joints to open. Many other incipient joints, not properly oriented, remain closed. No joint study thus truly reflects what is really there and/or the proper relations between joints. The fact that the best-developed joints in one outcrop are less prominent elsewhere reflects local conditions. The typical joint pattern is of two mutually-perpendicular joint sets parallel and perpendicular to slope and two additional sets that cross them diagonally.

Chapman, C.A. and Rioux, R.L. 1958. Statistical study of topography, sheeting and jointing in granite, Acadia National Park, Maine. *American Journal of Science*, vol. 256, pp. 111-127.

Keywords: Maine, topography, joint control, sheeting joints, granite

The paper attempts to interrelate jointing and sheeting with topographic effects of stream and glacial erosion. Both biotite and hornblende granites are present; the hornblende variety is more resistant. The rock is petrographically uniform and medium grained. The area is glaciated and ice movement was parallel to present valley trends. Slope measurements from maps were plotted on stereonet equivalents. Sheeting roughly conforms to present topography. It conforms least at low elevations where it is less steep than the slope. Most of the sheeting is pre-glacial, but some is parallel to ice-cut surfaces, indicating glacial or post-glacial age. The fact that sheeting surfaces are more closely spaced on ridge tops than on ice-cut slopes favors the unloading hypothesis. When sheeting and slope diagrams are compared, the sheeting diagram representing pre-glacial topography, a change in valley trend of 25 degrees as well as increased post-glacial asymmetry are shown. This study indicates that joints partly control topography and topography partly controls jointing. Valley walls parallel major joint sets.

Cloos, Ernst. 1965. Experimental analysis of fracture patterns. *Geological Society of America Bulletin*, vol. 66, pp. 241-256.

Keywords: experimental work, modelling

The paper describes laboratory experiments to make fractures. The medium is clay. The clay is placed on a piece of wire cloth on a flat surface and the edges and corners are pulled or pushed in various ways (with and without rotation) to produce the various patterns. Cloos gives four real world examples of increasing complexity and matches the field pattern with his experiments.

DeGraff, J.M. and Aydin, A. 1987. Surface morphology of columnar joints and its significance to mechanics and direction of joint growth. *Geological Society of America Bulletin*, vol. 99, pp. 605-617.

Keywords: basalt, propagation, morphology, columnar joints

The paper presents new observations of surface morphology of columnar joints and their interpretation in terms of kinematics. Columnar joints are caused by thermally-induced tensile stress. Cracks originate from flaws, such as voids or large grains, and the point of origin is usually marked as a hole or inflection in the crack surface. Linear breaks in the surface are called hackle; analysis of hackle and plumose structure indicates joint growth direction. The flows/columns appear to be divided into bands. Each band is a crack, showing that columns develop incrementally. Each crack propagates continuously. All observed crack origins are at intersections with adjacent cracks: in the basal portions of flows, they are on the lower side, and in the upper portions, they are on the upper side. All cracks grow into the flow. Plumose structure is discussed in some detail with reference to propagation. Crack terminations are also discussed. Criteria for determining crack growth direction are also given. New cracks originate along old ones because that is where stress is greatest. Propagation is usually at a small angle to the existing crack. Upward growth (or downward) is limited by decrease in stress and resistance to fracture from the heat and ductility of the lava. Cracks grow/occur sequentially as well as incrementally. Cracks/joints are studied in single-tiered, double-tiered and multi-tiered flows, and the above criteria and theories are applied. Downward growth from flow tops is greater than upward growth from the bottoms due to greater heat loss. Fan-shaped patterns of columns have a different origin than vertical columns.

Delaney, P.T., Pollard, D.D., Ziony, J.I. and McKee, E.H. 1986. Field relations between dikes and joints: Emplacement processes and paleostress analysis. *Journal of Geophysical Research*, vol. 91, pp. 4920-4938.

Keywords: propagation, Colorado Plateau, sedimentary rocks

Past indiscriminate application of dike emplacement theories led to this study of the field relations between dikes and joints which has resulted in a new theory for generating fractures during dike emplacement. The presence of closely-spaced joints adjacent and parallel to dikes suggests the former result from dike emplacement. Various mechanisms, including induced pore pressure increases, differential stress and thermal expansion during heating, are evaluated but none can form adjacent features over the distances required. Thermally-induced pore pressure increases, however, could generate such fractures in some cases. They conclude that the most likely process is "Tensile stresses caused by the wedging action of the magma...beyond the tip of a dike" (pp. 31-32). Both field and laboratory work support this conclusion. The longer the dike, the wider the zone of emplacement-induced, parallel fractures. The use of dike orientation to determine paleostress directions is discussed and pitfalls are described.

Ehlen, J. 1976. *Joint analysis in Glen Canyon National Recreation Area.* Fort Belvoir, Virginia: U.S. Army Engineer Topographic Laboratories, ETL-0073, AD A-033 330, 16 p.

Keywords: joint orientations, joint density, sedimentary rocks, remote sensing

Fracture patterns were delineated on stereo air photos. Joint orientations were analyzed using rose diagrams, and joint density was analyzed using a grid and contour method. Changes in orientation patterns between rock units indicate changes in stress through time. The results indicate that different rock units have different joint densities and orientation patterns, and that the different units can be differentiated on the basis of fracture orientation and density data derived from air photo analysis.

Ehlen, J. and Zen, E. 1986. Petrographic factors affecting jointing in the Banded Series, Stillwater Complex, Montana. *Journal of Geology*, vol. 94, pp. 575-584.

Keywords: lithology, joint spacing, grain size, mafic igneous rocks, Montana

Joint spacings for two mutually perpendicular joint sets were measured in each of five sample sites in gabbronorites and anorthosites. Joint density ranges from three to thirteen joints per square meter for the mafic rocks and from one to six joints per square meter for the felsic rocks. Joint spacing varies from 1-128 cm in mafic rocks (average: 4-65 cm) and from 1-300 cm in felsic rocks (average: 9-144 cm). Layer thickness ranges from one to six meters. Mineral mode and "clump size" consistently show strong relations with joint density and mean joint spacing; the higher the mafic mode and the larger the mafic clumps, the greater the joint density and the smaller the mean spacing. Felsic grain size decreases with increasing joint density. Layer thickness shows no relation with mean spacing for either joint set, with joint density or with mineral mode. Cooling and unloading could account for most of the differences in joint density because volumetric thermal expansion for pyroxene is about 50% more than for calcic plagioclase, but volumetric compressibility of pyroxene is about 50% less. The initiation of microcracks leading to joints may thus be favored by petrographic contrasts within the rock.

Engelder, T. 1985. Loading paths to joint propagation during a tectonic cycle: An example from the Appalachian Plateau, U.S.A. *Journal of Structural Geology*, vol. 7, pp. 459-476.

Keywords: sedimentary rocks, New York, rock mechanics, propagation, classification

The purpose of the paper is to describe four loading paths that lead to joint propagation in sedimentary basins and to give an example using the Devonian Catskill Delta in New York. Loading paths are plots of horizontal principal stress vs. depth of burial. Because joint sets have different orientations, it is assumed that they result from different loading paths. In addition, the Catskill rocks are assumed to have different loading paths to propagation because siltstones and shales have different mechanical properties. The general geology of the area is described. Several different treatments indicating the large number of possible loading paths are discussed. The author chose to address four end-member loading paths that lead to tensile fracture: hydraulic joints, tectonic joints, unloading joints and release joints. The two former types propagate during burial or at the maximum depth of burial and the two latter, during uplift and erosion. Hydraulic joints are caused by abnormal pore pressures during burial. Tectonic joints also form at depth under the influence of high pore pressure, but develop only during tectonic compaction. Unloading joints develop with little or no abnormal pore pressure when more than half the overburden has been removed. Release joints form in response to removal of overburden during erosion and are fabric controlled (i.e. they are normal to tectonic compression). Previous work by the author and other workers on joint set development in the Catskills is reviewed. These joint sets are classified as defined above; no hydraulic joints are thought to exist because depth of burial was too shallow. Hydraulic fracturing is discussed, however, and the results from industrial hydrofracting and analysis of the surface morphology of tectonic joints are used to explain some of the relations between the Catskill joint sets. Unloading and release joints are also discussed and the results of this discussion are also applied to the appropriate joint sets.

Engelder, T. 1987. Joints and shear fractures in rock. In *Fracture Mechanics of Rocks*, edited by B.K. Atkinson. London: Academic Press, pp. 27-69.

Keywords: microcracks, propagation, fracture mechanics

The paper presents a review of jointing, beginning with a brief historical summary of research. He then proceeds to look at isolated cracks, multiple cracks and shear fractures, and also looks at present debates regarding the formation and propagation of joints. Most microcracks and joints propagate as mode I (tensile) cracks. There are three kinds of microcracks: grain boundary, intergranular, and intragranular. Intragranular cracks are often jagged, and occur along cleavage planes. Microcracks occur in two ways—with a uniform distribution or oriented and associated with joints, faults, etc. Tensile stresses that form microcracks result from thermal or mechanical processes. Many microcracks heal and the healing rate is different for different minerals. The point of origin of individual joints can be determined from the plumose patterns on their surfaces. Many initiate at discontinuities such as fossils, bedding planes, or large microcracks. Rupture patterns in glass are described as they refer to mainly sedimentary rocks. Cracking can occur intermittently through time as stress varies. Even healed/sealed cracks can recrack. Fluid pressure in a joint must exceed pore pressure in the rock for cracking to occur. Mode I propagation occurs by twisting and tilting out-of-plane whereas shear failure follows a plane of high shear stress (Mode II or Mode III). The latter process involves formation of (oriented) microcracks, propagation and linking of these cracks and finally, large-scale shear failure, often accompanied by cataclasis. Clouds of microcracks at an acute angle to the fracture are often an indicator of shear. Extension shear fractures do occur—they can usually be identified by fibrous growth in the filling perpendicular to the joint plane. Random joint patterns on an outcrop scale develop in association with unloading and weathering. There are three basic loading conditions that lead to fracture: high shear stresses leading to shear failure (no depth restriction), the generation of abnormal fluid pressures (probably deep), and thermal elastic contraction during uplift and erosion (shallow). The latter two produce mode I cracks. Shear fracture requires far greater stresses than the production of extensional joints, approximately four times the tensile strength of the rock. Such stresses are not common on a regional scale, thus shear fractures are not regional. Engelder (1985)[4] identified four types of joints: tectonic, hydraulic, unloading and release. The two former result from abnormal fluid pressure and the two latter from thermal-elastic contraction. Unloading joints are controlled by tectonic stress at the time of denudation or by residual stress within the rock. Depth of propagation is probably 200-500 m.

Gay, S.P., Jr. 1972. *Fundamental characteristics of aeromagnetic lineaments, their geological significance, and their significance to geology.* Salt Lake City, Utah: American Stereo Map Company, 94 p.

Keywords: remote sensing, aeromagnetic data, Colorado Plateau, sedimentary rocks

The book is intended more as a manual describing a technique rather than as a presentation of new geological information. The purpose is "...1) to demonstrate that aeromagnetic lineaments map earth fractures, some of which appear on the earth's surface as faults, 2) to set down the fundamental characteristics of these fractures and fracture sets, and 3) to examine the implications of these disclosures to present geological thinking" (p. 1). Aeromagnetic lineaments are disruptions in contour patterns such as breaks or sudden changes or alignments of highs and/or lows. The lineaments are viewed and studied using stereo aeromagnetic maps. Aeromagnetic lineaments tend to occur in well-defined sets and also tend to be vertical or horizontal faults, not thrust faults. Examples of the coincidence of lineaments and known faults are given. Because sets of lineaments have very similar orientations in Arizona and the Paradox Basin, Gay concludes that there is a small number of fundamental fractures that occur everywhere; the fractures are Precambrian. From this he deduces that boundaries of geologic features are not random. He also suggests that lineaments are associated with intense regional metamorphism. The similarities in orientation in the Paradox Basin and Arizona are related to regmatic shear patterns and he suggests the use of stereo aeromagnetic maps as the means to relate the many local studies that have been done.

Gerrard, A.J.W. 1974. The geomorphological importance of jointing in the Dartmoor granite. In *Progress in Geomorphology*, edited by E.H. Brown and R.S. Waters, Institute of British Geographers Special Publication No. 7, pp. 39-50.

Keywords: granite, S.W. England, joint orientation, landform, theory

The paper begins with a general description of joints in granite, Dartmoor granites in particular. There are two types of horizontal joints: 1) primary, "normal," stress-release joints corresponding to Cloos's L joints, which are often mineralized and 2) secondary, dilation (compressional) joints caused by removal of overburden in association with developing topography. The second type are known locally as "pseudobeds." Orientation data from previous workers is summarized. Gerrard shows north-south and east-west to be the preferred directions; these are considered primary. Primary joints would control landform development, particularly drainage patterns. Details of the groups of rock outcrops, locally known as tors, are

[4] Engelder, T. 1985. Loading paths to joint propagation during a tectonic cycle: An example from the Appalachian Plateau, USA. Journal of Structural Geology, vol. 7, pp. 459-476.

controlled by the joint-controlled drainage blocks with compressional domes between. There are three types of tors: summit, valley side/spur and emergent. Summit tors occur where relative relief is more than 100 m within 800 m of the tor. Mean slope angle is probably important as well. Joints must be open to be exploited by weathering, and the opening of joints as the landscape develops could be due to rejuvenated streams cutting into the domes. This would allow the most intense jointing in summit areas, which is the case; joints would then tend to open parallel or perpendicular to the contours. Generally, the predominant joint directions in non-summit tors follow this pattern.

_______. 1978. Tors and granite landforms of Dartmoor and eastern Bodmin Moor. *Proceedings of the Ussher Society*, vol. 4, pp. 204-210.

Keywords: granite, S.W. England, landform, joint spacing

The paper is concerned with the detailed relations between individual rock outcrops (tors). Statistically, emergent tors are smaller, have gentler slopes at their bases, and are different from valley side/spur and summit tors. The height difference between valley side/spur and summit tors is not significant. Differences in maximum slope between valley side/spur tors and the other types are significant, but not between summit and emergent tors. The intensity of horizontal jointing differs between the three types. Vertical joints are more widely spaced on emergent than on summit or valley side/spur tors; the difference is significant. Weathering along variably-spaced vertical joints would produce a variable weathering front and thus different tor shapes. The weathering front is nearer the surface on summits and deeper near slope bases. Valley side/spur and summit tors occur where the joints are closer, the weathering front more variable, and where surface processes are sufficiently intense to remove weathered material. Emergent tors may be chance exposures.

_______. 1982. Granite structures and landforms. In *Papers in Earth Studies, Lovatt Lectures, Worcester*, edited by B.A. Adlam, C.R. Fenn and L. Morris. Norwich: Geo Abstracts Ltd., pp. 69-105.

Keywords: granite, joint spacing, S.W. England, landform, rock mechanics

The purpose of the paper is to view the characteristics of granite with respect to their physico-chemical and mechanical nature. Granite structures, including sheeting joints, A-tents, laminae, vertical joints, headings, microfractures, microcracks and rift and grain, are discussed briefly. Unloading as the cause of sheeting joints is difficult to test because the same arguments can be used for unloading and for primary structures. Most people accept unloading, but the corollary is that many vertical joints would then have to be secondary. Vertical joints are usually tension fractures. Microfractures are feather joints. Dearman, Baynes and Irfan (1978)[5] define seven types of microcracks. Rift is the easiest splitting direction; grain is at right angles to rift and is the second easiest splitting direction. Both are independent of flow lines and sheeting, and are parallel to fluid inclusions and microfracture concentrations. Various aspects of granite jointing, including orientation, spacing, joint surfaces, aperture thickness, infill material, water and continuity, are discussed. Fracture spacing is probably the most important factor defining granite landscapes. Rocks with discontinuous fractures are stronger than ones with continuous fractures. Landforms reflect the interaction between rock strength and geomorphic processes. Relations between the physical properties of

[5] Dearman, W.R., Baynes, F.J. and Irfan, T.Y. 1978. Engineering grading of weathered granite. Engineering Geology, vol. 12, pp. 345-374.

jointed rock and the characteristics of joints can be analyzed three ways: the finite element method of mathematical modeling, the construction of physical models, and observations of behavior in the field. Strength of joint surfaces can be addressed as unit stiffness across and along the joint and shear stress along the joint. In eastern Bodmin Moor, the tors form a rectilinear pattern—the east-west alignment of tors is favored by narrower joint spacing in this direction. The three types of tors represent a continuum in evolution. Landscape and tor evolution is discussed, as described in Gerrard (1974).

Glynn, E.F., Veneziano, D. and Einstein, H.H. 1979. The probabilistic model for shearing resistance of jointed rocks. In *Proceedings of the 19th U.S. Symposium on Rock Mechanics (Stateline, Nevada)*, compiled by Y.S. Kim. Reno: University of Nevada-Reno Press, pp. 66-76.

Keywords: mathematical modelling, failure, joint spacing, slope stability

The paper addresses the effect of discontinuity geometry on slope stability. The attitude, spacing and persistence of discontinuities are considered random. The paper describes a mathematical model for failure along fractures. Fractures are generated by computer, and the en echelon path of least resistance (route of most likely failure) in a given stress field is calculated. The greater the mean joint spacing, the more likely that failure will occur along individual joint planes. Joint spacing, joint length and rock cohesion appear to be the most important parameters controlling failure.

Grillot, J.-C. and Razack, M. 1985. Fracturing of a tabular limestone platform: Comparison between quantified microtectonic and photogeological data. *Tectonophysics*, vol. 113, pp. 327-348.

Keywords: France, remote sensing, limestone, data analysis

The purpose of the paper is "...to examine jointly fracture genesis and statistical inference of fracture frequencies considered at various scales..." (p. 328). The study area is in south-central France. The fractures are identified by age (using orientation data); there are four tectonic phases. Different fracture densities occur in the different carbonates; fractures in marly rocks are more closely spaced than those in carbonates with lithographic textures. Orientations are constant, though, substantiating the suspected tectonic origin of the joints. A model for fracture genesis is presented. Fracture intensity, which is not defined, is determined from 1:15,000 scale air photos and 1:1,500 enlargements of same; different scales apparently refer to study area size and/or to the field based vs. air photo parts of the study. Air photo-derived data is considered to be the population, and ground data is the sample. Ground data uses magnetic north and photo data, geographic north; because accuracy is ± 5 degrees, the same as magnetic deviation, the data are not corrected. The multivariate technique used to evaluate the data is correspondence analysis, a procedure similar to principal component analysis. This analysis shows that, quantitatively, there is no relation between field- and photo-derived data; the photo-derived data emphasize north-south and east-west orientations whereas 60-80 degrees and 100-130 degrees are prominent in the ground data. They conclude that "This analysis indicates that either technique provides a relatively homogeneous set of information about the fracturation spatial distribution regardless of the surface scales considered. However, it also shows a divergence in the two approaches when fracture directional frequencies (intensities) are concerned" (p. 347). This study indicates that, in well-exposed rocks, regional or areal interpolation of fracture patterns from sparse outcrops is justified.

Hancock, P.L. and Engelder, T. 1989. Neotectonic joints. *Geological Society of America Bulletin*, vol. 101, pp. 1197-1208.

Keywords: fractures, sedimentary rocks, contemporary stress, joint spacing

In this paper, the authors summarize their own previous work on neotectonic joints in New York, southeast England and northern France, east Arabia and northern Spain in order to draw a composite picture of neotectonic joints. These are comparatively simple joints formed at shallow depths. They are typically vertical extension fractures or, rarely, steep to vertical conjugate sets parallel to or symmetric about extension fractures. They tend to be larger and more open with wider spacing between them than earlier, tectonic joints. They are thought to result from burial followed by unloading and, because they are young, to reflect contemporary stress fields. The authors test this combination of characteristics and hypotheses in a more complicated part of the Valley and Ridge near State College, Pennsylvania, with very good results. The value determined using the neotectonic joints was within the range of values reported for other nearby areas. With respect to joint spacing, the authors find that spacing is controlled by previously reported characteristics (i.e. bed thickness, lithology, etc.), but they also found in the Spanish area, that joint spacing became wider with increasing elevation. In addition, these joints tend to be evenly spaced in unfractured rock and more irregularly spaced in previously fractured rock.

Harland, W.B. 1957. Exfoliation joints and ice action. *Journal of Glaciology*, vol. 3, pp. 8-10.

Keywords: glaciation, sheeting joints, stress release

There are two senses in which all joints can be considered as resulting from pressure release: 1) many joint systems develop very late and 2) removal of overburden by denudation "...so modifies the stresses in the rock that predetermined joints are made more evident (e.g. by opening)" (p. 8). The characteristics of sheeting joints are listed. Sheeting is best exposed in quarries (i.e. artificial, not natural, exposures) and dies out within a few tens of feet below the surface. Exfoliation tends to develop best in massive rocks lacking a closely-spaced tectonic joint system. Not all joints paralleling the land surface are sheeting joints; some are tectonic as well. A new mechanism for producing sheeting joints associated with glacial retreat is proposed as an additional, not alternative, mechanism to unloading due to decrease in ice thickness. He suggests that if the ground below the glacier is not frozen initially, when the ground freezes as the ice retreats, the conditions favoring exfoliation are accentuated.

Harris, J.F., Taylor, G.L. and Walper, J.L. 1960. Relation of deformational fractures in sedimentary rocks to regional and local structure. *American Association of Petroleum Geologists Bulletin*, vol. 44, pp. 1853-1873.

Keywords: sedimentary rocks, Wyoming, structure, bed thickness, lithology

The purpose of the study was to determine which factors govern fracture occurrence and concentration and to use this data to interpret geologic structure. Lithology was considered the most important factor. They determined density per square yard, amongst other things, and normalized density data by bed thickness. Density appears to be simply the number of fractures in a square yard. They determined that in a given rock type "...the concentration of fractures is in approximate inverse proportion to the thicknesses of the individual units" (p. 1856). Lithology was normalized in a similar manner and it was found that the more brittle the rock, the greater the fracture density. These figures were used as defined by the datum bed to relate different areas. The only joints used are normal to bedding and usually only one or two sets are present in a given area. The influence of rock type is less evident than that of bed thickness. The dominant fracture sets were related to structure in that one was well-developed on one side of an anticline and the other set on the other side of the anticline. Specifically, density in an area was determined to be controlled regionally, but can also be modified by local structure.

Hencher, S.R. 1987. The implications of joints and structures for slope stability. In *Slope Stability*, edited by M.G. Anderson and K.S. Richards. London: John Wiley and Sons, pp. 145-186.

Keywords: methodology, slope stability, engineering

The characteristics of discontinuities must be taken into consideration in engineering site investigations. Discontinuity is defined as a break or boundary that marks a change in the engineering characteristics of the mass. Types of discontinuities are defined and discussed, and their geotechnical aspects are listed. The types are: tectonic joints, faults, sheeting joints and lithological boundaries. Stability analysis requires knowledge of their distribution, geometry and engineering properties. The data needed on the discontinuities are: orientation, spacing, persistence, roughness and waviness, wall strength, aperture, filling, seepage, number of sets and block size. This information can be obtained by using photo interpretation procedures, by mapping surface exposures, or interpreting drill cores and bore hole data. Field mapping is the best way. Line surveys or windows are suggested as the best methods of measurement; the author cautions against 'over-statistical' and highly objective approaches. "Clearly the most suitable method for collecting data for a particular project will depend on the nature of the problem, the quality of the exposure, the resources available for investigation and the experience and expertise of the personnel involved" (p. 157). Two examples of stability analysis are given. Stereographic projection and numerical methods were found particularly useful in the analysis.

Hoagland, R.G., Hahn, G.T. and Rosenfield, A.R. 1973. Influence of micro-structure on fracture propagation in rock. *Rock Mechanics*, vol. 5, pp. 77-106.

Keywords: propagation, microcracks, experimental work, sedimentary rocks, fracture mechanics

This paper establishes the existence of the process or damage zone around propagating crack tips. They studied the Salem limestone and the Berea sandstone by measuring the energy dissipated by fracturing (R) using high resolution fractography and acoustic detection techniques. The experimental procedure is described. Load-displacement records are separated into three regions: Region I is more or less linear and represents elastic behavior; Region II is non-linear with increasing stress, but no crack extension; and Region III is characterized by decrease in load and increases in displacement which indicate crack growth is occurring. The R value represents the asymptotic limit, the point at which the propagation curve levels out and the crack grows at a relatively constant rate. Maximum R values occur in different planes for the two rocks; the sandstone values are much larger than the values for limestone. There is also some temperature dependence for the values of R in sandstone. The presence of water reduces R for both lithologies. Acoustic emission data indicate the presence of numerous cracks surrounding the crack tip. Microscopic study of the samples shows cracks propagate through the softer matrix for both lithologies. The formation of the damage or process zone can explain the observed pattern of R values. Evidence for this is based on observations and measurements of acoustic emissions, nonlinear compliance, permeability, x-ray studies and direct observations. Their model is described in detail and its implications are discussed.

Hobbs, W.H. 1911. Repeating patterns in the relief and in the structure of the land. *Geological Society of America Bulletin*, vol. 22, pp. 123-176.

Keywords: fractures patterns, joint orientations

Repeating patterns of lines are most obvious where there is little vegetation and where frost action is the dominant weathering process. The patterns occur in scale hierarchies. At the largest scale, the patterns are caused by joints. Drainage follows the joint patterns. The repeating patterns are not the same everywhere and tend to change (mainly in orientation) abruptly. Patterns caused by other features, such as folds, can obscure the joint patterns. Smaller scale repeating patterns tend to be composite, e.g. the line of a trough is continued by a stream segment. On a smaller scale, the lines that are repeated are called lineaments. Hobbs points out, by reference to the literature, that a fracture field exists throughout North America, with fractures oriented according to the cardinal points as well as northwest and northeast. When such a distinct pattern is not apparent, it is often because there are a multitude of fractures; the apparent randomness is caused by series of individual north-south, east-west, northeast/southwest and northwest/southeast patterns being superposed with some variation in orientation. He shows that the North American fracture field pattern also occurs in Europe and Africa and that it is thus a world-wide pattern. He believes it was caused by "...continued secular cooling of the planet" (p. 164). Joint systems do continue to develop through time, however. Joints and faults are only distinguished on the basis of scale. The elements in the repeating patterns are subequally spaced. Pre-existing fracture structures control denudation.

Holman, W.R. 1976. *The origin of sheeting joints: A hypothesis.* Unpublished Ph.D. dissertation, University of California at Los Angeles, 75 p.

Keywords: sheeting joints, theory, microcracks, topography

This thesis focuses on the influence of topography on sheeting because it is most amenable to analysis. Various load conditions are modeled and the results indicate that "...only a large near surface expansion with fractures according to the maximum-principal-strain criterion, which is not generally accepted, produces the observed pattern of sheeting" (p. 5). Tension fractures originate only near convex ridge crests, whereas those due to compression occur first beneath valleys; sheeting commonly originates on dome flanks. The release of grain-scale residual strain by microcracking is suggested as the mechanism. Sheet thickness is unrelated to topographic slope.

Holst, T.B. and Foote, G.R. 1981. Joint orientations in Devonian rocks in the northern portion of the lower peninsula of Michigan. *Geological Society of America Bulletin*, vol. 92, pp. 85-93.

Keywords: Michigan, limestone, joint orientations, data analysis

The purpose of the study was to investigate regional joint patterns in the mid-continent where tectonic activity is limited. All measurements were in limestones and shales, mainly in the former. One hundred orientations are measured per outcrop. A total of 4787 joints were measured in 43 localities. Holst and Foote tested reproducibility and found the result statistically acceptable. General observations at the outcrops were also made, and, with respect to orientation (similar to joint control), these impressions were often found to be in error when the data were evaluated. The data were plotted on standard rose diagrams in five-degree increments—only vertical joints were included (4552). Four joint sets were identified. There was no relation between either mean orientation or presence/absence of a given set and lithology, age or location. The attempt to relate the joint sets to known structural features in the area was relatively unsuccessful. Two orthogonal sets may be tension joints related to folding.

Hudson, J.A. and Priest, S.D. 1979. Discontinuities and rock mass geometry. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, vol. 16, pp. 339-362.

Keywords: mathematical modelling, joint spacing, data analysis, United Kingdom, engineering

The purpose of the research is to develop an approach to the study of discontinuities that will lead to the development of rational measurement techniques. The paper presents the results of a theoretical, statistical analysis which is validated by measurements from ground photographs. The results are that joint spacing frequency is a function of scanline orientation (when the joints are measured in sets), that joint spacings have a negative exponential distribution, that the frequency distribution of block areas is a Bessell function, that the area frequency distribution is insensitive to orientation assumptions, and that actual area distributions could have been predicted from the frequency measurements along scanlines.

International Society for Rock Mechanics (ISRM), Commission on Standardization of Laboratory and Field Tests. 1978. Suggested methods for the quantitative description of discontinuities in rock masses. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, vol. 15, pp. 319-368.

Keywords: methodology, rock mechanics, engineering

The purpose of "suggested methods" is to achieve some measure of uniformity, not to define standard procedures. Fractures, or discontinuities, are addressed in terms of orientation, spacing, persistence, roughness, wall strength, aperture, filling, seepage, number of sets and block size with respect to information obtainable from three different procedures: 1) photogrammetric methods, 2) outcrop description, and 3) drill hole and core description. Scope, equipment needed, procedure and additional pertinent information are discussed for each subject area.

With respect to orientation, it is suggested that measurements to the nearest 5 degrees are adequate. They suggest 150 measurements, although opinions of those they consulted varied from 80 to 300! They also recommend using 10-degree bands on rose diagrams. Because orientations and dips of sub-horizontal joints are inherently unreliable, rose diagrams are not recommended to display them. Roses misrepresent the data by exaggerating large concentrations and suppressing small ones. Equalarea nets are another way to display data. A photogrammetric method of obtaining orientation data is also discussed.

The line survey method is recommended for measuring joint spacings. The line should be at least 3 meters long, ten times the mean estimated spacing. Measuring tape and compass are not essential. Blasting-induced fractures should be excluded. Descriptors are given for ranges of spacings. Minimum, maximum and modal spacing should be recorded.

Persistence is one of the most important parameters, but is also one of the most difficult to quantify. A list of descriptors and ranges is again provided. Termination data, i.e. how the fracture ends, should be recorded wherever possible. Waviness causes problems when determining persistence. They recommend assuming 100% persistence when in doubt.

Roughness is important with respect to shear strength, but its importance declines as aperture or filling thickness increases. Roughness can be defined in terms of large scale undulations (waviness) and smaller scale features (unevenness). The former are too large to be sheared off. Minimum, most common and maximum roughness should be recorded. Several methods of obtaining roughness are discussed.

Aperture refers only to open joints. They suggest measurement using the line survey method and that modes should be recorded for each set. With respect to fillings, the finest fraction is most important because it controls long- term shear strength. Fillings should be described in terms of fracture geometry, filling type, filling strength and seepage.

Estimation of seepage characteristics are very important because seepage rate is roughly proportional to hydraulic gradient and to relevant directional permeability. Suggested descriptors and ratings are provided.

The number of fracture sets is usually determined simultaneously with orientation measurements. The authors recommend, as above, up to 150 orientations are needed to determine number of sets. Systematic sets should be differentiated from nonsystematic ones.

Block size is determined by a combination of number of sets, spacing and persistence. Small block size results in mechanical behavior similar to that of soils. Block size should be determined by volumetric joints counts, i.e. counting the number of joints in a set distance.

The determination of these same ten parameters from drill core is also detailed. The authors recommend that when there is doubt as to whether a fracture is natural or not, it should be assumed to be so, so that the resultant determination is the most conservative possible.

Jahns, R.H. 1943. Sheet structure in granites: Its origin and use as a measure of glacial erosion in New England. *Journal of Geology*, vol. 51, pp. 71-98.

Keywords: *New England, sheeting joints, glacial erosion, crystalline rocks*

Sheeting tends to conform to the granite surface, except on slopes, particularly south slopes, where slope is greater than sheeting dip. This is due to oversteepening of these slopes by glacial plucking. The characteristics of sheet structure are closely related to the amount of glacial erosion. The rocks include granite, granite gneiss and quartz monzonite. Sheeting is similar in all three, as well as in anorthosites, paragneisses and all other intrusive rocks of intermediate and acid composition. As depth increases, sheeting becomes progressively thicker, more horizontal and less irregular. Sheeting is best developed on the most massive rocks and the least jointed granites are the most thinly and regularly sheeted. The quaquaversal dips of sheet structure are independent of primary structures. Sheeting does not conform to the original shape of the intrusion. Sheet structure not only parallels the surfaces of hills, but also that of hollows and valleys. Sheeting extends to a depth of at least 320 feet. Sheeting joints are flat to undulatory. Theories of origin are discussed and Jahns concludes the most probable cause is dilation upon relief of primary confining pressure. Sheeting is pre-glacial, but "secondary," post-glacial sheets parallel to the new land surface also exist; these are of minor importance. He notes that "...sheeting broadly controls topography when denudation is relatively slow and long continued but is reoriented when strongly concentrated erosion by water or ice creates relatively rapid topographic changes" (p. 84). The greatest amount of granite removed by glacial plucking and abrasion is where the rocks are intricately jointed. There appears to be a quantitative consistency between thickness of sheets and depth. Sheeting varies with mineralogy and texture.

Kieslinger, A. 1960. Residual stress and relaxation in rocks. *Proceedings of the International Geological Congress, 21st Session (Norden)*, part 18, pp. 270-276.

Keywords: sheeting joints, stress release

All rocks have been compressed at some time in their history and when the stress is released the rocks "relax" very slowly, so that residual stress remains. Sheeting is parallel to the surface, independent of petrofabrics, extends to depths of 40-50 m and cannot occur in jointed rock. The surface that sheeting parallels is not necessarily the present one. Rift, grain and hardway (quarrymen's terms) extend only to 40-50 m depth as well; they also result from relaxation of residual stress.

Knapp, R.B. and Knight, J.E. 1977. Differential thermal expansion of pore fluids: Fracture propagation and microearthquake production in hot pluton environments. *Journal of Geophysical Research*, vol. 82, pp. 2515-2522.

Keywords: mathematical modelling, propagation

The paper quantitatively evaluates a process in which "...cracks may be produced by differential thermal expansion between fluid in isolated fluid-filled pores and encasing minerals" (p. 2515). Pore pressure increases with increasing temperature, decreasing effective pressure at the boundary. Fracturing occurs when effective pressure becomes less than the tensile strength of the rocks. Isolated pores were chosen because they comprise about 90% of total pore space in crystalline rocks. Failure occurs at shallower depths when pores are elliptical (rather than spherical) because of stress concentrations at the ellipse tips. A geothermal gradient greater than 14 degrees/km is required for failure. The paper refers to fracturing in the host rock rather than in the pluton itself; failure occurs along a zero effective pressure front that propagates outward from the pluton at a decreasing rate through time. The front continues to propagate long after the pluton is cooled. Propagation of microcracks produces microearthquakes.

Kobayashi, T. and Fourney, W.L. 1978. Experimental characterization of the development of the micro-crack process zone at a crack tip in rock under load. *Proceedings of the 19th Annual Symposium on Rock Mechanics (Stateline, Nevada)*, compiled by Y.S. Kim. Reno: University of Nevada-Reno Press, pp. 243-246.

Keywords: propagation, microcracks, experimental work

The paper presents a method for recording crack growth under incremental stress and describes the cracks so formed. Rock behavior under stress has been shown to be different from that of steel or polymers. Minute hairline cracks propagated in a branching manner along grain and inclusion boundaries as well as along structural irregularities in the rock so that the area covered increases with distance. New cracks formed at greater stresses took new paths.

Kranz, R.L. 1979. Crack growth and development during creep of Barre Granite. *International Journal of Rock Mechanics and Mining Science and Geomechanics Abstracts*, vol. 16, pp. 23-35.

Keywords: microcracks, experimental work, propagation

The purpose of this study was to try to understand how cracks grow and interact in a rock under constant stress as a function of time and to relate this to the common creep curve. Terms are defined and the experimental procedures are described. The cracks were produced in the rock and analyzed using Scanning Electron Microscopy. There were distinct differences between cracks in stressed and unstressed rock. Micas and minerals next to micas contained the most cracks in both stressed and unstressed specimens. Almost all cracks were tensile. The crack aspect ratio distribution shifts to lower values with increasing stress and time. Cracks appear to close down to an equilibrium value once stress is removed. Stress and time tend to increase crack length. Loading induces new cracks and makes old cracks grow. The number of cracks increased with stress until creep began when they appeared to decrease in number. Crack orientation tends to change over time, moving to ±45 degrees to stress direction. Creep theories are discussed. New cracks do develop under constant stress. Under constant strain, growth is limited by the rate of stress applied, but under creep, the rate of corrosion can decrease crack growth. Crack tip strength is normally the controlling factor but the presence of cleavage planes can change this.

_______. 1983. Microcracks in rocks: a review. *Tectonophysics*, vol. 100, pp. 449-480.

Keywords: microcracks

This is a review paper summarizing recent work on the subject. The author suggests the bibliography may be the most useful part. He concentrates on microcracks as entities rather than as how they affect the physical properties of the rock, stressing morphogenesis, kinematics, dynamics and statistical studies. There are three kinds of microcracks: grain boundary, intergranular and intragranular. Each is discussed. Generation is discussed as either mechanically or thermally induced. Six mechanical mechanisms are described: twin interactions; release of stored energy associated with kink bands and deformation lamellae; cleavage separations; stress concentrations near cavities, grain boundaries and crack tips; mismatches in elastic compliances; and grain translations and rotations. Differential thermal expansion and contraction also produce microcracks. The amount of quartz in the rock is important below the alpha/beta transition because of differential thermal expansions between quartz and feldspar. Thermal gradients and differential cooling also cause microcracking. Fracture kinematics and dynamics are discussed in terms of different kinds of stresses, crack paths, interactions and growth, and crack localization. Microcrack statistics are discussed in terms of orientation, length, width, aspect ratio, and theoretical studies. A table summarizing the observational data available is given. Finally, future directions are discussed. He suggests the study of slow crack growth and the use of acoustic techniques will become more important.

Ladeira, F.L. and Price, N.J. 1981. Relationship between fracture spacing and bed thickness. *Journal of Structural Geology*, vol. 3, pp. 179-183.

Keywords: joint spacing, bed thickness, sedimentary rock

Previous work has indicated a linear relation between bed thickness and fracture spacing. The authors found this suspicious, particularly as all the earlier work was done on beds < 1.5 m thick. Degree of rock deformation, as well as lithology and bed thickness, affect joint spacing. Fracture development in competent beds is related to the thickness of adjacent incompetent layer; the greater the thickness of the incompetent bed, the higher will be the number of fractures per meter in the competent layer. Mean fracture spacing in graywackes and limestone is sensibly independent of bed thickness where beds are > 1.5 m. They suggest the two groups of fractures (> 1.5 m bed thickness and < 1.5 m bed thickness) result from different mechanisms. Fractures in the thicker beds are thought due to hydraulic fracturing. The actual mechanism is discussed. They suggest that increase in grain size would be associated with increase in spacing with reference to hydraulic fracturing.

Lee, F.T., Miller, D.R. and Nichols, T.C., Jr. 1979. The relation of stresses in granite and gneiss near Mount Waldo, Maine, to structure, topography, and rockbursts. *20th U.S. Symposium on Rock Mechanics (Austin, Texas).* Littleton, Colorado: U.S. National Committee on Rock Mechanics, Society of Mining Engineers, pp. 663-669.

Keywords: sheeting joints, Maine, stress release, joint spacing, crystalline rock

The purpose of the paper was to identify rock properties that promote rockbursts. The granite plutons intrude eugeosynclinal metasedimentary rocks. Sheeting is well developed and vertical joints are rare. Sheets are 3-20 cm thick, increasing to three meters and more at depths of 7-15 m. Subhorizontal shear zones are associated with upper levels of sheeting. Sheeting is thought to be due to unloading because it cuts the youngest igneous rocks in the area and effects glaciated and unglaciated terrains equally. Horizontal stresses are greater than can be explained by rock load and magnitude differences occur between sheets; the greater the block size, the greater the stress. Stresses in the mountain site are much greater than in the valley site; this is contrary to conventional analyses. The bedrock adjusted to erosional loading changes by strain relief, which decreases inward. "The tendency for these rocks to relax was restrained by an interlocking fabric of anisotropic mineral grains, cohesion between grains, shear stresses along fractures, and stiffness variations among different rock types" (p. 666). "Sheeting is a consequence of the slow upward expansion (decompression) brought about by erosional unloading" (p. 666). The depth at which sheeting occurs varies and is controlled by the magnitude of in situ stress, stress concentrations due to topography, rock strength and deformation properties (including jointing and foliation) and the effects of ground water. The latter can explain why stress is less in the confined valley site, because rock properties, including tensile and compressive strength, hardness and crystallographic control of fractures, can be affected by small amounts of water. Water can extend sheeting fractures.

Leonard, R.J. 1929. Polygonal cracking in granite. *American Journal of Science*, vol. 18, pp. 487-492.

Keywords: granite, Arizona, polygonal cracking, weathering

Polygonal jointing is normally attributed to cooling, but recently has been shown to result from weathering as well. Granite outcrops are castellated, typical of arid regions. There is some rounding, but the aspect is generally blocky. Faces of large blocks and outcrops show polygonal cracking. The rock is varnished and/or case hardened. Cracks average one to two inches in width and depth. The cracks have rough surfaces. As weathering proceeds, the less resistant material behind the polygons disintegrates and polygonal slabs fall away. The important factors in induration probably were 1) infiltration of silica from solutions circulating along joints and local granulation and 2) solution and recyrstallization of quartz on joint surfaces. The cracks are probably primary and have been opened and widened by weathering.

Lewis, W.V. 1954. Pressure release and glacial erosion. *Journal of Glaciology*, vol. 2, pp. 417-422.

Keywords: glaciation, stress release, sheeting joints

This is a leisurely paper, much more 19th than 20th century in style. The point is that as a result of rummaging around beneath and behind glaciers, the author concludes that fractures parallel to the ground surface develop when the ice and its pressure are removed, i.e. stress release is residual. He is not sure whether the fractures are pre-existing or not.

Marre, J. 1986. Primary joints and associated intrusive veins and sheets. In *The Structural Analysis of Granitic Rocks*, translated by J. Renouf. New York: Elsevier, pp. 42-52.

Keywords: granite, structure, classification

This section of a chapter gives a classification of primary joints, i.e. those associated with emplacement. Primary joints are easily distinguished from later joints by their relations to the granite and their fillings, i.e. mineralization or sills. They are all extension joints and are caused by the decrease in volume that accompanies crystallization. Parallel joints, those that parallel the flow planes, are horizontal joints and develop in sheets, laccoliths and the apical parts of domes. They are distinguished from exfoliation with difficulty. Cross joints are perpendicular to flow lineation, form early and are very irregular. They result from several causes and only occur in border zones. Longitudinal joints are normal to flow planes and parallel to flow lineation. They develop later than cross joints but their cause in uncertain. They are possibly the result of relaxation after cross joint formation. Diagonal joints also occur. They are present as conjugate sets at 45 degrees to flow lineation and result from shear.

Mastella, L. 1972. Interdependence of joint density and thickness of layers in the Podhale Flysch. *Bulletin de L'Academie Polonaise des Sciences*, vol. 20, pp. 187-196.

Keywords: joint density, bed thickness, sandstone, Poland

The purpose of the study was to determine whether regional differences in stress fields are genetically related to jointing. Measurements were taken only in valley bottoms, in similar fine- to medium-grained sandstones and in areas with the least local tectonic disturbance. Previous work in this rock unit has shown that when other parameters are constant, joint density is independent of layer thickness, as is joint spacing in individual joint sets. Because of this, differences in the density/thickness ratio are attributed to differences in the regional stress pattern. The data must be normalized to a standard thickness to show this, however. The relationship between joint density and bed thickness was found to be logarithmic, not linear.

McQuillan, H. 1973. Small-scale fracture density in Asmari Formation of Southwest Iran and its relation to bed thickness and structural setting. *American Association of Petroleum Geologists Bulletin*, vol. 57, pp. 2367-2385.

Keywords: Iran, joint density, bed thickness, limestone

Previous work is well summarized, indicating no quantitative work on the relation between fracture density and bed thickness had been done. Fracture density is defined as the number of fractures intersecting a perpendicular 100-foot line. A basic assumption was that density would vary considerably with structural position and bed thickness. Data was collected in three anticlines, mainly in thinner, rather than thicker, beds (because of exposure). Bed thickness was treated in ranges. Fracture density was found to be constant for a given bed thickness, azimuths are random and uniformly distributed, and there are no density variation trends associated with either local or regional structures. The scattergrams show consistent decrease in fracture density with increasing bed thickness. The relationship is logarithmic rather than linear. Because of the scatter in azimuths and the relation between density and thickness, the author concludes that the origin of fractures must be related to diagenetic as well as to tectonic influences.

Moeyersons, J. 1977. Joint patterns and their influence on the form of granitic residuals in NE Nigeria. *Zeitschrift fur Geomorphologie*, vol. 21, pp. 14-25.

Keywords: Nigeria, joint distribution, weathering, granite

There are two types of residual hills in the area: 1) saprolite covered hills and 2) bare rock domes, castle koppies and tors with deep weathering pockets. The joint pattern is cuboidal. One set of curved joints flattens with increasing depth and a second flattens upward. The second set is less curved than the first. These joints are not caused by pressure release because they link up with the other joint sets and are not related to topography. This indicates structural control of the hills. Saprolite is separated from solid rock by joint planes as are weathering zones. Horizontal joints are virtually absent from the deep weathering pockets. With reference to cuboidal joints, weathering penetrates most rapidly to where horizontal joints cross each other. Where horizontal joints are convex, weathering penetrates more slowly because density is greater on top of the hills. The curved joints will guide water away.

Mohammad, M.R. 1987. Jointing and airphoto lineations in Jurassic limestone formations of Al-Adirab area, Tuwayq Mountain, adjacent to Al-Riyadh, Saudi Arabia. In *International Geomorphology 1986, Proceedings of the 1st International Conference on Geomorphology, Part II*, edited by V. Gardiner. Chichester, England: John Wiley and Sons, pp. 359-365.

Keywords: lineations, remote sensing, Saudi Arabia, limestone

The paper relates ground-based fracture patterns to air photo lineation patterns. There are three joint systems, consisting of six sets and five significant lineation orientations or sets. Most of the lineations are short (less than 2000 m) suggesting they are local rather than regional. Lineations are mostly subparallel to joints. Correlation between joints and lineations is poor which could be due to their short length.

Narr, W. and Suppe, J. 1988. Joint spacing in sedimentary rocks. *Geological Society of America Abstracts with Program*, vol. 20, p. A319.

Keywords: joint spacing, sedimentary rocks, frequency distribution, bed thickness

The purpose of the paper is to test Hobbs' (1911) theory of joint spacing, i.e. that joints develop sequentially with shorter, later joints developing between earlier ones. They find a linear relation between bed thickness and spacing. The spacing distribution is log normal, not multi-modal as predicted by Hobbs' theory. They determine that mechanical properties are more important in controlling spacing than lithology and that a Hobbs-type distribution can be produced if flaws in the rock control joint spacing.

Nemat-Nasser, S. and Horii, H. 1982. Compression-induced nonplanar crack extension with application to splitting, exfoliation, and rockburst. *Journal of Geophysical Research*, vol. 87, pp. 6805-6821.

Keywords: propagation, sheeting joints, experimental work

The purpose of the paper is to study kinked-crack growth from pre-existing closed cracks under overall far-field compression. The kinks grow steadily until a certain length is reached, then they "sprout." Length becomes unbounded if tension normal to compression is present. The kinks are thought to develop as a result of relative sliding along crack faces. If grown near a free surface, the kink shows no tendency to grow toward that surface, but parallels it as in sheeting or exfoliation. This apparently only occurs when there is a small amount of tension normal to the compression; under large compressive loads, crack growth is toward the free surface. "...a suitably oriented pre-existing crack of 10-20 cm may grow into a sheet fracture under compressive tectonic stresses of about 20-50 bars, the required tension normal to the sheet fracture being only about 0.5-2 bars" (p. 6816).

Nemat-Nasser, S., Keer, L.M. and Parihar, K.S. 1978. Unstable growth of thermally induced interacting cracks in brittle solids. *International Journal of Solids and Structures*, vol. 14, pp. 409-430.

Keywords: joint spacing, propagation, theory

The numerical analysis presented in this paper derives from the hot, dry rock work where it is essential to be able to predict spacing, distribution and length for fractures induced by the hot water. Other applications of these results are also noted. Two temperature profiles comprise the basis for analysis: one assumes a homogeneous, isotropic inelastic solid with initially uniform temperature and the other takes account of convection. The profiles more or less represent end members of the possible situations. Both interacting and non-interacting cracks are analyzed with reference to stability. The mathematical derivation is given and numerical examples are presented. The results indicate that given a series of parallel, equally-spaced cracks (although there is no reason to assume initial spacing is either equal or periodic), at a critical load parameter, every second crack stops growing and the growth of the remaining cracks occurs at a faster rate. This regime persists until another critical state is reached and the results here depend on which temperature profile is in force. For the non-convective profile, all cracks that have already stopped growing and every second "still-growing" crack snap closed and the remaining cracks snap to a finitely longer length. Spacing increases by four times. For the convective model, only those cracks that stopped growing at the first critical state snap closed and all remaining cracks snap to a longer length. Spacing thus doubles. It is the interaction between cracks that leads to unstable growth.

Nichols, T.C., Jr. 1980. Rebound, its nature and effect on engineering works. *Quarterly Journal of Engineering Geology*, London, vol. 13, pp. 133-152.

Keywords: elastic rebound, propagation, sheeting joints

The purpose of the paper is to clarify the nature of the rebound process and to identify the direction for future work. Examples of rebound in different geological terrains are given. In the near surface, horizontal stresses are many times greater than vertical stresses; this relationship decreases with depth. Stresses on different types of rocks at depth are different. Release of residual strain in one type of rock could thus increase horizontal stress on a neighboring, different type of rock. Stress fields in shallow rocks are thought to result from

(a) present-day tectonic loading caused by plate movement and/or (b) locked-in residual strain. Option (a) alone is not adequate to explain many geologic situations and thus Option (b), redefined as release or rebound, must be invoked. Stored strain energy is released by work done by removal of external constraints, by the creation of new surfaces, possibly by the addition of fluids and by thermal cycling. These are accomplished by uplift, denudation, water penetration and diurnal and seasonal thermal changes, respectively. Rebound fractures are "...usually easily distinguished..." (p. 139). They are non-tectonic, extensional and "...are usually subparallel to the local topography, increasing in density toward the surface, very local in extent and normally have very little to no filling material" (p. 139). They may either crosscut or terminate against tectonic fractures. Distribution is related to lithology and proximity to free surfaces. Most researchers assume these fractures are due to unloading and weathering processes that occur as free surfaces are exposed by removal of external confining loads. The author contends that if this is all there is to it, there would be no time-dependent fracturing. He shows, using Coulomb's failure criterion, that measured stresses in shallow rocks are inadequate to cause observed shear failure, which suggests the presence of local stress concentrations. He suggests "...that *initial near-surface fracturing results from* propagation of micro-fractures caused by either viscoelastic rebound or the long-term release of stored strains and internal stress distribution of a residual stress field. Failure, then, should be a function of time-dependent strain criteria. As fracturing progresses, permeability increases and rock strength decreases, thereby allowing accelerated chemical weathering. The resulting increased penetration of ground water, in turn, may enhance further crack growth. Near surface thermal gradients also cause stress concentrations that aid in crack growth" (p. 146).

Nickelson, R.P. 1976. Early jointing and cumulative fracture patterns. *Proceedings of the First International Conference on the New Basement Tectonics*, Utah Geological Association Publication No. 5., pp. 193-199.

Keywords: fractures, sedimentary rock, joint spacing, spatial patterns

The purpose of this paper is to summarize some of "...the descriptive and historical attributes of fracture patterns that have been established by field studies" (p. 193). The author shows, by reference to the literature and to his own work, that fracture patterns are cumulative, in that most patterns are composite throughout time; persistent, in that they are not erased by later events; and polygenetic, in that propagation results from different types of stress and is either direct or indirect. Indirect genesis refers to later upward propagation of vertical fractures in sedimentary units. Nickelson states that fracture frequency is controlled by lithology, bed thickness and tectonic position, but that topographic effects may be reflected in near-surface patterns as well. He gives ranges in joint spacing as: coal - millimeters, shale - centimeters, sandstone - meters. He also suggests that fractures as viewed on air photos occur in zones and that ground observations are restricted to collecting data within zones. Different regions of fracturing are described. These are: coastal plains, characterized by simple orthogonal systems formed prior to lithification; cratonic platforms or horizontal plateaus, where "Complex cumulative patterns of overprinted, orthogonal, fundamental joint systems denote a history of differently oriented, low magnitude stress differences that have resulted in extension fractures of great regional continuity" (p. 197); non-metamorphic fold-thrust mountain belts which are more complex than the above, containing the same types of patterns with the addition of fractures formed by folding; metamorphosed and penetratively deformed mountain belts where patterns are simpler because flowage has wiped out the effects of earlier fracture patterns; and finally, old basement exposed in the craton or block uplifts which reflect the epitome of cumulative fracture patterns.

Nur, A. and Simmons, G. 1970. The origin of small cracks in igneous rocks. *International Journal of Rock Mechanics and Mining Science*, vol. 7, pp. 307-314.

Keywords: microcracks, experimental work, mathematical modelling

The paper attempts to determine the origin of microcracks and to see if they can be induced by drilling. Microcracks are defined as equal to or shorter than characteristic grain dimensions and are associated with grain boundaries. Mathematical models are used to show that differential thermal expansion and differential compressibility are possible sources of microcracks and that such cracks should be expected in the presence of quartz because of its properties. With respect to induced cracking, cracks only develop near the stress level at which discing occurs.

Oen, I.S. 1965. Sheeting and exfoliation in the granites of Sermersoq, South Greenland. *Meddelelser om Gronland, Kommissionen for Videnskabelige Undersogelser I. Gronland*, vol. 179, pp. 1-40.

Keywords: granite, Greenland, sheeting joints, theory, glaciation, geomorphology

The geomorphological history of the area is summarized. The differences between large-scale sheeting and small-scale exfoliation are discussed. Sheeting is considered to be secondary; similar primary structures also exist, but they are not named. The characteristics of sheeting in the study area are: 1) it is dependent on glacial geomorphological forms, 2) it extends to depths beyond which weathering and insolation are effective, 3) it is unrelated to primary granite structures, 4) there are no displacements or sills along the sheets, 5) well-developed sheeting exists only in rocks "...poor in pre-existing open joints..." (p. 12) and 6) thickness increases from a few decimeters to two meters with depth. Sheeting is parallel to glaciated valley walls and also parallels the surface in the bottoms of broad valleys and in cirques; in general, it parallels the land surface. It is best developed where there is high relief. Because not all such areas have sheeting, it must have developed after glacial sculpture was completed. "The only discernable relation between sheeting and other jointing in the granite seems to be that they tend to exclude each other" (p. 18). In areas without pronounced relief, sheeting and vertical joints occur together, but neither is well developed. Because sheeting occurs in many rock types, it cannot be attributed to textural or compositional characteristics of the rocks. Sheeting only seems to occur in rocks other than granite, however, near granite massifs which are usually post-tectonic. Such sheeted granites may represent an early stage in disintegration, which implies the later opening of vertical joints and the rounding of joint blocks by weathering. The cause is probably dilation, which operates hand in hand with weathering. Hypotheses of origin are discussed and discarded. A new theory, that the mass deficiency of granites due to their lower density produces gravitational forces that cause the granite to rise, which in turn results in vertical compression, is suggested. As uplift slows or ceases, decompression occurs and sheeting results. This theory allows sheeting to develop only once unless the uplift occurs again in a similar manner, i.e. sheeting is not a continuous process. Small-scale exfoliation, such as the development of sheeting in quarries, would result from release of small residual stresses. Such stresses are greater than what would result from unloading. If erosion is sufficiently rapid, decompression could occur slowly and sheeting would never develop. Stoping is a likely method of emplacement for granites that develop sheeting in this manner, because they would remain free of open joints.

Olson, J. and Pollard, D.D. 1988. Interpretation of joint sets based on fracture mechanics. *Geological Society of America Abstracts with Program*, vol. 20, pp. A318-A319.

Keywords: rock mechanics, propagation, en echelon joints

Numerical solutions are applied to elastic boundary problems and fracture mechanics in order to study the effects of regional and local stresses on crack interactions, propagation, trace length and aperture. With respect to en echelon joints, the greater the stress, the straighter the joints; regions of closely-spaced parallel joints are produced. Lower values of stress produce hook-shaped tips -- when there is very little difference between maximum and minimum stress, the hooked/curved tips converge, resulting in a disc-like pattern. A new mechanism for en echelon fractures is suggested.

_______. 1989. Inferring paleostresses from natural fracture patterns: a new method. *Geology*, vol. 17, pp. 345-348.

Keywords: propagation, paleostress, Utah

This paper relates the shapes of overlapping joint traces to differences between greatest and least compressive stresses. The method is based on the premise that state of stress in certain environments is more important than rock fabric. The curved paths of the crack tips are due to mechanical interactions. Where there is remote differential compression, crack paths will be straighter; where stress is tensile, curved paths result. This is because the direction of shear is opposite in the two cases. Where there is no stress differential, paths diverge, converge, then approach each other asymptotically. There is no divergence when the stress differential is positive, i.e. compressive, and path convergence is reduced. The path becomes increasingly planar with increasing compression. Tensile stress produces exaggerated divergence and convergence so that the cracks meet at T-intersections. Local stress (driving force) must be greater than remote stress to produce the curved paths. These interactions decrease with increasing joint spacing. A field example is given.

Parker, J.M., III. 1942. Regional systematic jointing in slightly deformed sedimentary rocks. *Geological Society of America Bulletin*, vol. 53, pp. 381-408.

Keywords: sedimentary rocks, New York, orientation

The purpose of the study was to formulate an adequate theory for the origin of systematic joints. Twenty-four quadrangels in eastern New York and northern Pennsylvania were studied. The rocks are mainly interbedded compact brittle shales and fine-grained tough sandstones. About 6000 joint orientations were measured. Most joints were vertical and joint spacing was quite close. The study was accomplished by first investigating the joint patterns in a small area and determining the degree of constancy. Three joint sets were identified. Set I is a conjugate set of straight, planar joints with a regional radiating pattern. Set II consists of curved and irregular joints perpendicular to Set I. Set III is more local than regional, but strike is regionally consistent. Second, the area of study was expanded so that the relations between jointing and other tectonic features could be evaluated. Because of the absence of consistent relations, all joint sets are thought to be independent of local and regional structures. Finally, the types of stresses producing these patterns were postulated and tested experimentally. This work indicated that Set I consists of shear joints that result from a combination of compression and tension. Set II consists of tension joints. The conditions under which Set III formed are less clear, but these joints are probably tension joints as well, but younger than Set II joints.

Peng, S. and Johnson, A.M. 1972. Crack growth and faulting in cylindrical specimens of Chelmsford granite. *International Journal of Rock Mechanics and Mining Science*, vol. 9, pp. 37-86.

Keywords: microcracks, experimental work, Massachusetts, granite

The paper begins with a brief, clear discussion of fracture theory in which they show that neither Coulomb nor Griffith theory can predict fracture orientation. Theory does correctly predict that growth occurs near (but not at) the ends of pre-existing cracks and is not in the plane of the pre-existing crack. The process of fracture is studied by a combination of experimental and laboratory work. A very detailed and precise fabric study of the granite, which included identifying different types of microcracks, measuring them, and evaluating them with reference to rift, grain and hardway, is presented. The planes are also identified petrographically. Different types of stress are studied on the samples. A lengthy discussion of the methodology/technique developed for measuring stress follows, as well as the experimental results. The results indicate that no matter what kind of stress is placed on the specimen, crack growth occurs parallel to rift. Crack patterns and densities are identified in the stressed specimens, but are not related to initial crack patterns or distributions. A theory of faulting called beam buckling is then proposed and derived mathematically. This theory fits the experimental results better than either Coulomb or Griffith theory.

Pincus, H.J. 1951. Statistical methods applied to the study of rock fractures. *Geological Society of America Bulletin*, vol. 62, pp. 81-130.

Keywords: fracture orientation, lithology, data analysis, New Jersey

The sampling areas are in gneisses, conglomerates and limestones of different ages, and the purpose of the study is to compare fracture patterns between lithologies. The geology of the area and the sample sites is described. Sample sites in gneiss were mainly road cuts, but there was apparently no confusion between natural fractures and disturbance caused by construction. Limestone sample sites are in quarries, and conglomerate sites are natural. He had problems finding exposures of adequate size. Measurement sites in adjacent rock types were located so that they were structurally related. All fractures were measured on small exposures but in larger ones, fractures were measured along traverses. Restrictions on measurement sites are listed. No spacing measurements were made, but in large quarries, joint spacing appeared to be related to lithology and to be closer in the more argillaceous rocks. Strikes and dips were plotted on rectangular coordinate paper. A grid was placed over the plotted points and the latter were counted by square; these counts are the data addressed statistically. This method allows frequency distributions to be determined directly by row and column counts. The amount of data needed was determined by collecting measurements in increments of 20, then plotting to see at what point the pattern stabilized. Different grid square sizes were also used. Sedimentary point patterns stabilized with fewer numbers of points than gneissic patterns. The Poisson Exponential Binomial Limit was used to evaluate the point patterns. Cluster patterns were resolved to form mean fracture planes for each cluster and these were also evaluated. The possibility of useful interpretation decreased as area size increased and distinctions became blurred and merged. Data on fractures were compared to bedding plane and foliation data to determine stress and age relations. This was done by comparing dihedral angles of mean fracture planes. Differences in rock type were evaluated in the same way and differences in fracture orientation and dip were found to be largely independent of rock type. It was determined that differences between sedimentary and gneissic patterns result from different stresses by comparing point patterns within rock types. Measurements on a few large fractures could not adequately characterize a locality. An attempt to erase the effect of late deformations by rotating the point patterns was made. It appears to work for the sedimentary rocks, but not for the gneisses. Pincus summarizes with a fracture history.

Piteau, D.R. 1973. Characterizing and extrapolating rock joint properties in engineering practice. *Rock Mechanics, Supplement 2*, pp. 5-31.

Keywords: Zambia, engineering, data analysis, sedimentary rocks

This paper defines joint properties and, by use of the example of a joint study in the Nchanga open pit mine, shows how these properties can be evaluated. Significant joint properties are: orientation and spatial distribution, continuity, intensity, surface asperities, genetic type and gouge. The detail line joint survey method is recommended for data collection because it gives more detail, is representative (particularly if lines are mutually perpendicular) and is more objective than other methods. Also, because it is a form of systematic sampling, the data are amenable to mathematical analysis. Possible errors are discussed: measurement errors, operator errors and errors due to including induced fractures. The technique used to analyze the data is based on the identification of structural regions and later extrapolation of patterns within these regions. Orientation data is evaluated using the method of cumulative sums and Manhattan diagrams to identify the structural regions. Corrections are then made to the data and sub-regions are identified. Joint sets are defined within structural regions according to angle and direction of dip. Extrapolation to other nearby areas can then occur. Repeated survey on a regular basis is recommended 1) to produce better extrapolation and 2) to convince management the procedure works.

Pollard, D.D. and Aydin, A. 1988. Progress in understanding jointing over the past century. *Geological Society of America Bulletin*, vol. 100, pp. 1181-1204.

Keywords: propagation, rock mechanics, theory

This paper is in two parts -- one summarizing papers on jointing that were published in Geological Society of America bulletin over the past 100 years and the other summarizing modern work on joints from the geometric and mechanical point of view. The history of thought concerning joints is presented chronologically by summarizing appropriate papers. They believe much of the confusion related to joints results from the lack of pertinent data and the absence of a sound conceptual framework, i.e. from using a tool that is not understood to explain something that is also not fully understood.

Fractures are defined in terms of opening. Mode I includes fractures that open perpendicular to the fracture surface. Modes II and III exhibit shear parallel to the fracture surface. Mode II fractures are perpendicular to the propagating front and Mode III fractures are parallel to it. Joints are usually mode I, whereas faults are mode II or mode III. There must be some relative displacement along joints however, because if there were not, they would not be visible. Joints and faults also differ because their stress and strain fields are different, they have different textures and fillings, and they accommodate strain differently.

Joint geometry is discussed in terms of the surface morphology of single joints, joints with multiple plumose structures, shape, dimension, spacing and density, and patterns of multiple joints. Various surfaces patterns on joint faces are described. These include origin, axis and hackle which, when combined, comprise plumose structures.

Kinematics is discussed with reference to propagation, propagation velocity, joint interaction, termination and intersection, and strain accommodation. The interpretation of surface patterns with respect to propagation of single joints is explained. Joint spacing can provide information on propagation because spacing widens in the direction of propagation for joint sets. The more overlap there is in en echelon joints, the wider the spacing between them is.

Joints normally terminate against discontinuities and the type of intersection can give information on age, stress and other related factors.

The mechanics of jointing are discussed in terms of initiation, propagation, propagation path, arrest, and mechanical interaction. Joints initiate at flaws because flaws perturb the stress field, causing local tensile stresses to exceed rock tensile strength. These flaws can be grain contacts, inclusions, pores and/or microcracks. The most effective initiation mechanism, however, is fluid pressure aligned perpendicular to remote least compressive stress. In this orientation, joints will happily propagate as long as fluid pressure is maintained. Propagation is controlled by the stress field at the crack tip and is related to joint opening. Mixed mode fractures will have smoothly-curved or sharply-kinked paths. Surface morphology is directly related to path. Arrest occurs when fluid pressure or stress decrease below critical values, when rock properties change, or when discontinuities are encountered. Mechanical interactions affect density and spacing. Each joint enhances propagation of its neighbor by inducing tensile stress at its tip. When tips overlap, the stress becomes compressive and growth stops. When deformation is mode II, this produces curved paths and joints converge. Some joints shield other joints as they grow, so joint sets necessarily consist of a few long ones and many shorter ones. The longer the joint initially, the greater the likelihood it will become longer and the greater the area of its shielding effect. This results in increased spacing between surviving cracks. The paper ends with a discussion of subject areas for future research.

Rats, M.V. 1962. Relation of fracture spacing to thickness of layer. *Doklady Akademiya Nauk SSSR*, vol. 144, pp. 622-625.

Keywords: bed thickness, joint spacing, Russia, sandstone

Three types of fractures are identified, but only one type shows any relation between spacing and bed thickness. These are in sandstone, and terminate abruptly at boundaries with siltstones and argillites. Joint spacing was measured by set; ten to twenty measurements were made per set per sandstone bed. The fractures were separated into two groups by dip, i.e. those greater than or less than 72 degrees. Both groups show a logarithmic relationship in the form of a = bMk. His analusis of data on limestone provided by others supports this relationship as do sources in the literature. The relationship is therefore assumed universal within a lithologic type.

Roberts, J.C. 1961. Feather-fracture, and the mechanics of rock-jointing. *American Journal of Science*, vol. 259, pp. 481-492.

Keywords: Wales, sedimentary rocks, joint surfaces, plumose structure

The purpose of the study was to evaluate and expand previous work on feather fracture, or plumose structure, on joint surfaces. The work was done in the South Wales coal field. The parts of the plumes are described as is the occurrence of feathers on joint surfaces in different kinds of sedimentary rocks. It is most common in flaggy sandstones. Feather fracture did not occur or was rare in fine and coarse grained rocks and in homogeneous ones. Possible origins are discussed and the mechanism of fracture is evaluated with respect to fracturing in steel. The author concludes that feather fracture is compressional, not tectonic and tensional, that it is analogous to "cleavage fracture" in steel, that it is controlled by lithology and that homogeneity, bed thickness and grain size are also important.

Robertson, A. MacG. 1970. The interpretation of geological factors for use in slope theory. In *Planning Open Pit Mines, Proceedings of the Symposium on the Theoretical Background to the Planning of Open Pit Mines with Special Reference to Slope Stability (Johannesburg, RSA)*, edited by P.W.J. Rensburg, The South African Institute of Mining and Metallurgy, pp. 55-71.

Keywords: slope stability, modelling, methodology, rock mechanics

Rock properties should be assessed by direct measurement in the field rather than by testing in the laboratory. Types of failure surfaces are described. Traditional line sampling is recommended, preferably on two mutually perpendicular faces, but it is compared only to area (or window) sampling. Size, number, spatial distribution and orientation are the most important joint properties. Trenches, slope faces or tunnels underground are recommended for data collection so that the effects of weathering are avoided. The greatest source of error is in the measurement of dip and strike; repeated survey showed dip error to be ± 5 degrees and strike error to be ± 10 degrees. Errors due to selection of joints to be measured are also important. A rather complicated method of analyzing the data involving many corrections to take care of various kinds of bias is described. The effect of correction was to increase the numbers of joints normal to the direction of sampling. Data were evaluated by structural region and sets were defined from computer printouts. The model is based on a statistically homogeneous and anisotropic distribution. Most of what goes into the model appears to be estimated, not real data. A formula for estimating joint density using the height of the sampling face is presented. This formula says about 100 joints per set are needed to estimate population density with 95% confidence within 20% of the true value. Area sampling produces better results than line sampling. Rock strength parameters are discussed as are the estimation of various rock and joint properties related to slope stability. The author concludes that estimation based on direct measurement is an adequate method, but that a great deal is not yet known.

Scott, I.D. 1913. The spacing of fracture systems and its influence on the relief of the land. *Gerlands Beitrage zur Geophysik*, vol. 13, pp. 164-260.

Keywords: joint spacing, New York, sedimentary rocks

Joints are defined as nearly vertical fractures. Spacing varies between and within lithologies, being widest in sandstone, intermediate in limestone and narrowest in shale. The concept of primary and secondary joints is described. Joints usually occur as two sets at right angles; one set is usually predominant. "In favorable areas the spacing of joints of at least two orders of magnitude within each series has been noted..." (p. 166). Joints are considered the "parents" of faults. General discussions on the influence of joints on topography and drainage are presented. He notes in the latter that spacing has received little attention and that is why he is addressing the subject. A long history of interest in joints is presented and the work of major contributors to the study of joints is summarized. This is followed in a second part by a field study of the joints in two areas in New York, one of limestone and the other of shale with interbedded limestone and sandstone. Although the pattern of jointing differs from layer to layer (i.e. variations in rock type) this does not mean the joints are not formed at the same time. Because of frost action, the influence of joints upon topography is greater in high latitudes. The purpose of the work was to see if the spacing was regular, as suggested by others previously. Joints were measured in sets, in both outcrops and quarries. Only joints that extend through the entire exposure were measured. The data were plotted as frequency histograms by set. In the shale, average spacing (actually modal spacing) is similar for the two sets (between one and two feet) and spacing at greater intervals tends to be multiples of that average spacing. Joint spacing in limestone was less clearly defined in that it was wider and more variable and the predominance of the basic unit was lower. Measurements were also attempted on photographs and maps; the results of both support the idea that joints are regularly spaced.

Secor, D.T., Jr. 1965. Role of fluid pressure in jointing. *American Journal of Science*, vol. 263, pp. 633-646.

Keywords: theory, fluid pressure, subsurface growth/initiation

Joints begin to develop in rock as soon as it is capable of brittle fracture, regardless of rock type. Jointing will develop in consolidated rock even in the absence of other types of structural deformation, and "...appears to reach its ultimate regularity and perfection..." (p. 634) in such situations. In most places, joints are independent of structure. Joint patterns are locked within the rock early in its history, and as only a few joints open upon exposure, the visible pattern is not necessarily representative of the rock itself. Most joints are considered tension fractures, but as such cannot develop at other than very shallow depths; the role of fluid pressure solves the problem. Griffith theory produces compressive stresses that are too low. "The Griffith theory itself introduces the assumption tnat fracturing occurs by growth of cracks in rock due to stress concentrations at crack tips" (p. 637). Theory excludes the effects of fluid pressure and the intermediate principal stress. He shows that if the effects of fluid pressure are considered, tension fractures can develop "...to a depth of several thousand feet" (p. 642). The effect of fluid pressure depends on weight of overburden; the greater the ratio, the deeper the tension fractures can occur. Using the same type of logic, he shows that open fractures can also exist at great depths.

Seeburger, D.A. and Zoback, M.D. 1982. The distribution of natural fractures and joints at depth in crystalline rock. *Journal of Geophysical Research*, vol. 87, pp. 5517-5534.

Keywords: subsurface data, joint spacing, joint orientation, crystalline rock

The study addresses various characteristics of fractures in bore holes in three different geographic areas. The characteristics studied are: whether statistically significant orientations can be identified, whether the number and/or orientations vary with depth, whether frequencies and orientations vary locally, and what relationship, if any, exists between observed fractures and regional stress and the geologic history of the area.

The technique used is based on the smoothness of the bore hole wall -- dark patterns appear where planar features occur. There are two disadvantages to the technique: 1) only a small portion of a fracture is observed and orientation may thus be highly inaccurate and 2) because the bore hole is vertical, vertical fractures are excluded. Fractures in bore holes tend to occur in clusters.

Data from wells drilled in the Mohave Desert show sandstone is much less densely fractured than quartz monzonite, that fracture density may be decreasing with depth (150-200 m) and that fracture density does not increase toward the San Andreas fault. There is no decrease in fracture density with depth in the South Carolina wells, each about 0.25 km deep, but horizontal joints tended to occur in the upper 300 m. These rocks are granodiorite. Orientations showed little consistency and surface measurements by Secor (1980)[5] support this. The third area is also in California near the San Andreas fault; it is in quartz monzonite. The holes are only about 220 m deep. Again, there is no tendency for fracture density to decrease with depth and there is also no increase toward the San Andreas fault. With respect to the latter, it appears that the wells closest to the fault in the two California areas are two kilometers distant, and that there is no tendency for fractures to be aligned parallel to the fault.

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[5] Secor, D.T., Jr. 1980. Geological studies in an area of induced seismicity at Monticello Reservoir, South Carolina. First technical report, contract no. 1-08-001-19124. Reston, Virginia: U.S. Geological Survey.

Overall, there was only a slight tendency for fracture density to decrease with depth but most fractures were steeply dipping, not horizontal. Fracture orientation was consistent throughout the holes, but varied considerably from hole to hole, indicating little to no relation with regional stress. Surface fracture patterns "...are probably a good indication of fractures in the upper kilometer of the crust" (p. 5533).

Segall, P. 1984. Formation and growth of extensional fracture sets. *Geological Society of America Bulletin*, vol. 95, pp. 454-462.

Keywords: California, propagation, theory, modelling, granite

The purpose of the paper is to explain why joints "...form sets, made up of many subparallel dilational fractures, each of finite length" (p. 454). The paper apparently refers to the same joints examined by Segall and Pollard (1983b). The joints formed as open, fluid-filled fractures; they are extension fractures with dilational displacements and with little evidence of shear. Much interpretation of theory indicates that joints should be single and of infinite length; such experiments assume constant stress and fluid pressure. The problem is viewed from the perspective of fractures propagating in sets rather than individual fractures that combine in some way later to become sets. Increases in crack length are virtually totally dependent on the increase in applied strain and the initial crack density. The paper concludes with a model of crack growth.

Segall, P. and Pollard, D.D. 1983a. From joints and faults to photo lineaments. In *Proceedings of the 4th International Conference on Basement Tectonics*, edited by I. Ramberg and R.H. Gabrielson. Denver, Colorado: Basement Tectonics Committee Inc., pp. 11-20.

Keywords: remote sensing, California, granite, faults

The paper looks, micro- and macroscopically, at fractures and air photo lineaments in the Sierra Nevada. The purpose is to determine the nature and origin of ground fractures, to illustrate the relations between ground data and air photo lineaments and to determine if ground displacements between lineaments are apparent. The air photo lineaments identified by Lockwood and Lydon (1975)[6] are used. There are three fracture domains, which are generally unrelated to lithology. All joints are dilational in origin. The fractures are mainly joints in one area and mainly faults in the other, although sheared filling that is compositionally the same in both areas indicates that the small faults began life as joints. By measuring displacement of aplite dikes across the gullies that form the lineaments, the same relations were determined to occur at air photo scales. Lineaments and fractures are parallel. Because the air photo patterns of the two types of fractures are virtually identical, it is suggested that interpretation of type of fracture should be made on the basis of field work as it cannot always be done from photos.

[6] Lockwood, J.P. and Lydon, P.A. 1975. Geological map of the Mount Abbot quadrangle, central Sierra Nevada, California, scale 1:62,500. Geologic Quadrangle Map GQ-1155. Reston, Virginia: U.S. Geological Survey.

_______. 1983b. Joint formation in granitic rocks of the Sierra Nevada. *Geological Society of America Bulletin*, vol. 94, pp. 563-575.

Keywords: California, granodiorite, stress, joint length

One purpose of the paper is to provide data on joints in granitic rocks. The second is to show that by measuring displacement across a joint, direct information on strain is obtained and that combined with density measurements, this allows constraints to be put on the initial stress environment. The data is outcrop scale and the rock is granodiorite. The joints were formed as dilational fractures. Some were filled with epidote and chlorite and some underwent minor shear at a later date. To determine strain, joint apertures were measured perpendicular to the joints along traverse. Joint spacing is variable. The small, filled hairline cracks were not measured. Their strain/stress calculations are comparable to experimental data. Long joints were found to restrain the growth of short joints such that short joints cease propagating when less than half as long as the long ones. As long joints grow, they interact with other long joints further and further away. This produces large numbers of short joints and few long ones. The authors also suggest that the reason joint spacing is not uniform in granitic rocks is because there is no mechanical constraint, such as bedding planes, on them.

_______. 1983c. Nucleation and growth of strike slip faults in granite. *Journal of Geophysical Research*, vol. 88, pp. 555-568.

Keywords: granodiorite, origin, California, faults

The paper describes the field relations of a series of fractures that have developed one from the other in granodiorite, which is not the way fractures and/or faults are normally considered to grow. The joints were initially dilational and were filled later. Stress orientation changed slightly in a second deformation, causing left-lateral slip on some of the filled joints. These continued to grow as secondary fractures near the tips which eventually linked the small faults into larger ones. This has important implications for experimental work because such work is usually done with unfractured material. If the scenario of this paper is common, then doubt should be cast on much experimental work.

Selby, M.J. 1977. On the origin of sheeting and laminae in granitic rocks: the evidence from Antarctica, the Namib Desert and the Central Sahara. *Madoqua*, vol. 10, pp. 171-179.

Keywords: sheeting joints, laminae, Antarctica, Africa, theory

In general, sheeting transgresses other joints and dikes. Spacing becomes greater with depth and averages 0.3-8 m. The sheets are nearly parallel. There are two theories of origin -- primary and secondary. With respect to Dartmoor in SW England, because topography on the edges of the moor is Quaternary and the sheets are Cenozoic, the unloading hypothesis is unacceptable. Sheeting in Quaternary glaciated valleys, however, does result from unloading. It appears more likely that sheeting is caused by initial compressive stress. A secondary origin for sheeting is probable for both areas studied.

"Laminae are scale, flake, flaggy or plate-like skins or shells of rock which are formed closely parallel to the surface of an outcrop" (p. 174). They are commonly one to five centimeters thick. They appear to develop in conformity to the surface. They occur in many rock types and climates and thus probably result from a variety of processes. Because laminae are thinner at their edges, they produce concavities. Lamination is a physical, not chemical, process but the precise cause(s) could not be identified. Chemical weathering may reduce the effectiveness of the laminae-forming processes and the ubiquitousness of laminae suggests they could be due to inherent properties in the rock, such as in-built stress.

Shaler, N.S. 1869. Notes on the concentric structure of granitic rocks. *Proceedings of the Boston Society of Natural History*, vol. 12, pp. 289-293.

Keywords: sheeting joints, insolation, granite

Concentric structures occur where vertical joints have the least effect, and thus provide access for weathering agents. The essential feature of sheeting joints is their curvature. Concentric structure is surficial, confined to the upper four or five feet. Insolation, which includes both seasonal and diurnal temperature changes, is the most likely cause of sheeting. It is also possible the separations result from chemical decay, but this is unlikely because chemical decay is not evident and the scales formed by such action are only one to two inches thick whereas the sheets are one to three feet thick. Dome-like forms are the result of this concentric structure.

Da Silveira, A.F., Rodrigues, F.P., Grossman, N.F. and de Mello Mendes, F. 1966. Quantitative characterization of the geometric parameters of jointing in rock masses. *Proceedings of the First Congress, International Society for Rock Mechanics (Lisbon)*, pp. 225-233.

Keywords: data analysis, rock mechanics

The paper describes the method used by the Portuguese National Civil Engineering Laboratory to quantify joint parameters. They do not feel that determining the distance between joints in a given set is of much interest; spacing is addressed as the number of joints over a given distance of rock surface. The orientations of individual joints are plotted on the upper hemisphere of a Schmidt net, a grid is superposed, and poles are counted in a 1% circle with grid intersections at the center. This data is contoured and a circular pattern of poles defines a joint set. Areas of homogeneity are verified by determining the number of joints in individual sets in different areas and using coefficients of variation to determine regularity in the distribution. Once the rock mass is known to be homogeneous, sets are identified from the joint density diagram. Joint set characteristics are then calculated -- strike, dip, area, thickness (probably aperture) and spacing. Examples of the technique are given.

Simmons, G. and Richter, D. 1976. Microcracks in rock. In *The Physics and Chemistry of Minerals and Rocks*, edited by R.G.J. Strens. London: John Wiley and Sons Ltd., pp. 105-137.

Keywords: microcracks, petrography

The purpose of the paper is to describe the petrographic characteristics of various kinds of microcracks and show that differences can indicate origin. They believe microcracks are produced by any process that raises local stress above local strength. Definitions are given and the procedures for making and "decorating" their special thin sections are described. The following types of cracks are identified, described and discussed: dPdT cracks, stress induced cracks, radial cracks about totally enclosed grains, concentric cracks about totally enclosed grains, tube cracks, thermal cycling cracks,thermal gradient cracks, shock-induced cracks, cleavage cracks, thin section cracks and cracks of unknown origin. Healed cracks are also briefly discussed.

Snow, D.T. 1968. Rock fracture spacings, openings, and porosities. *Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers*, vol. 94, No. SM-1, pp. 73-91.

Keywords: subsurface data, joint spacing, engineering

The paper presents a method for determining subsurface permeability for grouting purposes which involves determining fracture permeability/spacing in bore holes. Although used in an applied manner, the method is based on certain assumptions: that there are only three sets of joint, that flow is laminar and that joint spacing is a Poisson distribution. If the data do not fit the latter, it appears that the interval is changed so that they do. Joint spacing increases and aperture decreases with depth, regardless of rock type. Neither spacing nor aperture appear related to rock type. Minimum spacing at 5 feet depth was 4 feet, and at 300 feet depth, 14 feet; these spacings are wider than those usually reported because measurements are usually made to include disturbed rock; disturbed rock was not included in this study. The decrease in permeability with depth is due more to decrease in aperture than to increase in spacing.

Spencer, E.W., 1959, Geologic evolution of the Beartooth Mountains, Montana and Wyoming, Part 2, Fracture patterns. *Geological Society of America Bulletin*, vol. 70, pp. 467-508.

Keywords: Montana, granite gneiss, remote sensing, Wyoming, joint orientation

The purpose of the study was to determine the fracture pattern, to identify variations in the pattern, and to relate it to regional tectonics. The structures of the Big Horn Basin and the Beartooth Uplift are described. All measurements were in granitic gneiss and only sites with more than 100 measurements were used for regional analysis. Joint orientations and dip were measured; there were no spacing measurements. Data are analyzed conventionally using stereonet projections, contouring and frequency histograms. This analysis indicated regional preferred orientations and also suggested that most fractures dipping less than 75 degrees are local aberrations or are due to tilting. The results show a remarkably uniform pattern on the southwest slope that is also weakly developed on the northeast slope. No preferred groupings are evident on outcrop scale, and variations between sample sites are as great as variations between different structural blocks.

Photo analysis of the southwest slope was also used. Possible sources of error are listed. Two sets of measurements of lineaments longer than 1/8 mile were made: 1) all lineaments and 2) those known to be fractures or faults. Orientations were plotted as histograms and rose diagrams. The results indicate that the photo study alone would lead to indefinite conclusions, but that used in conjunction with the ground measurements, it corroborates conclusions based on field work. Strong trends in one data set may not be strong in the other, but do exist. Measuring large numbers of lineaments (thousands) on photos produces results "...more nearly consistent..." (p. 496) with ground measurements.

Relationships between fractures and dikes and fractures and folds are briefly investigated; a relationship between folds and fractures is possible. Variation in the pattern is probably due to a nonuniform stress field. Four major trends exist for the uplift as a whole. These are considered the oldest as they outline major blocks.

Swain, M.V. and Hagan, J.T. 1978. Some observations of overlapping interacting cracks. *Engineering Fracture Mechanics*, vol. 10, pp. 299-304.

Keywords: experimental work, glass, propagation

This paper presents the results of experimental work that supports previous work, some of which is theoretical. The authors show how indentation-induced parallel cracks growing toward each other deviate toward each other when the tips overlap. They used soda-lime glass, different crack separations and different distances between indentations. Stress intensity increased on the cracks growing away from the two growing toward each other. They state that these relations apply in all cases, except possibly where cracks are widely spaced. These results may be of significance to the proposed mechanism of cleavage step formation in brittle solids.

Tharp, T.M. 1987. Conditions for crack propagation by frost wedging. *Geological Society of America Bulletin*, vol. 99, pp. 94-102.

Keywords: ice formation, propagation, theory

The purpose of this paper is to examine a model for frost damage on the basis of propagation of cracks and joints by pressure exerted by ice formation. It is theoretical and moderately mathematical. Minimum crack lengths are required for propagation, depending on the size and shape of the crack. Short-term freezing with unconfined water will propagate joints in all types of rocks. Short, tapered cracks will not propagate with short-term freezing in crystalline rocks. Igneous rocks are thus considered most resistant to frost damage. Grain size may exert control in that cracks can be no longer than the grain and if the grain is too small, there is no propagation. Crack length and geometry are more important than the effects of time and temperature. The author concludes that much disintegration in strong rocks must be chemical.

Thorpe, R. 1979. *Characterization of discontinuities in the Stripa Granite—time-scale heater experiment.* University of California, Berkeley, Lawrence Berkeley Laboratory (LBL) for the U.S. Department of Energy, LBL-7083, 107 pp.

Keywords: Sweden, subsurface data, data analysis, granite, nuclear waste disposal

The paper is one of a pair describing related experiments at different scales. Both papers are concerned with discontinuities in granite as part of a larger study about nuclear waste disposal. The study area is an abandoned mine and the work is cooperative between Sweden and LBL. The experiment "...is designed to simulate the interactive thermal effects of an array of waste canisters over a period of 12 years" (p. 5). The overall objective is to evaluate far-field effects of heating on rock to improve modelling capabilities. Vertical displacement, temperature, stress-strain and in situ fluid pressure were measured in bore holes. Fractures were mapped at 20:1 scale on the drift floor and from core. The data sets were found to be comparable by statistically comparing frequencies. Thorpe's frequencies, however, were 2-3 times less than actual frequencies, because only fractures longer than 0.3 m and open fractures were measured. Average frequency was 6 per meter; maximum, 14 per meter. Four, major, through-going fractures were identified. All data were combined and analyzed statistically. Four sets were identified. Orientation, size, spacing (lognormal) and infilling were studied. Past stress environment and on-going deformation are discussed. He concludes that the methodology is adequate and sound, but that more, perhaps more detailed, work is required to improve the statistical analysis.

Trainer, F.W. 1973. Formation of joints in bedrock by moving glacial ice. *U.S. Geological Survey Journal of Research*, vol. 1, pp. 229-235.

Keywords: glaciation, theory, joint orientation

The paper "...presents the hypothesis that stress applied by a moving glacier opens joints in the underlying bedrock" (p. 229). Joints were measured (dip and strike) at 21 localities (Sierra Nevada, New York, and Mount Desert, Maine) in granite or rhyolite, sandstone, dolomite and limestone. One hundred joints were measured at most localities; road cuts were included. Horizontal joints were measured in the sediments but only steeply-dipping joints in the granite. The measurements were plotted on stereonets and analyzed using Spencer's (1959) method. Joints tend to be similar to glacial striations (also measured) in orientation, at a large angle to or at about 45 degrees to striations. This pattern is present in the contoured data regardless of area and rock type. Trainer needs to know which joints are regional before concluding any of his joints are glacial in origin, but does not have this data. He believes the abundance of sets supports the idea of glacial origin. Implications of the theory with respect to structure, geomorphology and ground water are discussed. With respect to the latter, he cites work that suggests glacially-induced fracturing results in shallow aquifers.

Verbeek, E.R. and Grout, M.A. 1982. Dependence of joint spacings on layer thickness in sedimentary rocks. *Geological Society of America Abstracts with Program*, vol. 14, p. 637.

Keywords: frequency distribution, joint spacing, sedimentary rocks, layer thickness

The purpose of the work is to describe mathematically the inverse relation between joint spacing and layer thickness in sedimentary rocks. A linear relation is usually used, but this predicts wider spacing for thin beds than is normally the case. They recommend a logarithmic relation plotted on log-log paper.

Whalley, W.B., Douglas, G.R. and McGreevy, J.P. 1982. Crack propagation and associated weathering in igneous rocks. *Zeitschrift fur Geomorphologie*, vol. 26, pp. 33-54.

Keywords: microcracks, propagation, weathering

The paper proposes that cracks form fundamental links between physical and chemical weathering mechanisms. The two processes work together. The paper addresses crack formation and extension in igneous rocks, the effects of cracks on bulk rock properties and the weathering that occurs in cracks. Crack propagation according to the Griffith criterion is discussed; the theory is not really applicable because 1) rocks are not adequately homogeneous, 2) cracks behave plastically at their tips, 3) arrays of cracks, rather than single ones, are probably involved, and 4) stress is often compressive, not tensile, as required by Griffith theory. Behavior of large rock bodies is probably more like the Mohr theory; and Griffith behavior is probably more applicable to breakdown of small pieces of rock. The presence of microcracks at the surface and their attenuating mechanisms are discussed. By allowing moisture access to rocks, fractures reduce rock strength -- this is how they control weathering. Porosity, permeability and capillarity are the important factors. Various physical weathering processes are discussed in terms of how they are controlled by cracks -- frost shattering, salt weathering, insolation and wetting and drying. Chemical aspects include the chemical environment in the fracture system, stress corrosion, and fracture formation by chemical weathering. Weathering within fractures, which is mainly chemical, is also discussed. They conclude that chemical and physical weathering really cannot be separated and suggest three types of cracks for subaerial weathering -- those produced by deep-seated processes, mineralogical concentrations that become cracks, and those extended by physical processes.

Wheeler, R.L. and Dixon, J.M. 1980. Intensity of systematic joints: methods and application. *Geology*, vol. 8, pp. 230-233.

Keywords: Appalachians, sedimentary rocks, joint intensity, data analysis

The purpose of the paper is to produce a statistically robust estimator of joint intensity. Intensity is defined as "...the surface area of systematic joints per unit volume of rock" (p. 230). Field methods for data collection based on their sedimentary Appalachian experience are recommended. Previously developed estimators are inadequate with reference to very large or very small spacings within a joint set, which tends to be a fairly common situation. Such irregularity is expected. Three more reliable methods are suggested: collecting very large amounts of data, using median spacing, and using the trimean (based on median and quartiles). Intensity rather than abundance is recommended for rose diagrams because the former is less biased. Offsets in measurement traverses are considered acceptable. The effects of joint size are included in their equation. There is comment and reply associated with this paper in which the authors are criticized for not addressing bed thickness and lithology. Wheeler's response is that this is done elsewhere and that this study was within previously determined and published constraints. He believes structure, bed thickness and lithology are the most important factors controlling joint spacing in the areas where he has worked.

Wheeler, R.L. and Stubbs, J.L., Jr. 1979. Style elements of systematic joints: statistical analysis of size, spacing and other characteristics. In *Proceedings of the 2nd International Conference on Basement Tectonics (Newark, Delaware)*, edited by M.H. Podwysocki and J.L. Earle. Denver, Colorado: Basement Tectonics Committee Inc., pp. 491-499.

Keywords: sandstones, joint spacing, data analysis

The authors attempt to determine whether joint sets differ significantly in properties other than dip and strike. They do this by using the method of style elements, which was originally developed by Hanson (1962, 1971)[7] for describing small folds in multiply-folded metamorphic rocks, non-parametric statistics and easily collectable field data. A style element is "...a field-observable aspect of a joint's size, intensity, orientation, shape or associated rock character" (p. 491). Data were collected at two outcrops in sandstones in the ranges of several meters thick. The effects of outcrop size are discussed. Joint sets were identified using lower hemisphere, equalarea projection. They evaluated 23 numeric and non-numeric variables and conducted two levels of statistical tests. Analysis of variance is used to determine whether there is more variation between than within sets and if there is, they determine where the difference lies. An arbitrary cut-off value is used and three variables are selected as significant—perpendicularity (relation to bedding planes), true depth, and joint spacing. The use of large, abundant joint sets is suggested for future work. Little difference was found between numeric and non-numeric variables on the first cut, but numeric variables performed better on the second cut. The authors conclude that there are significant differences between joints sets in addition to orientation and make suggestions for future work, including the use of additional numerical techniques.

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[7] Hanson, E.C. 1962. Strain facies of the metamorphic rocks in Trollheimen, Norway. Unpublished Ph.D. dissertation, New Haven, Connecticut: Yale University, 206 pp.; and Hanson, E.C. 1971. Strain Facies. New York: Springer Verlag, 220 p.

Wise, D.U., Funiciello, R., Parotto, M. and Salvini, F. 1985. Topographic lineament swarms: clues to their origin from domain analysis of Italy. *Geological Society of America Bulletin*, vol. 96, pp. 952-967.

Keywords: Italy, shaded relief maps, methodology, lineament orientation

The paper describes a different approach for looking at lineaments. The technique involves "...mapping limits of strong development of specific azimuthal sets of the most prominent linear elements..." (p. 952). Lineaments are defined by length and width. The data were derived from photos taken from four different directions of the undersides of Defense Mapping Agency shaded relief maps. The negatives were then printed upside down. The data were digitized, and a sample was selected from the total and analyzed using frequency histograms and rose diagrams. The petals of the roses were identified so that domain boundaries could be identified and then the individual lineaments were fitted into their domains. Calculations and statistics were then done. The reliability of the method was tested in several ways and it was found to be comparable to other, more conventional, methods. It is suggested that problems in some published lineament studies could result from not looking at spatial characteristics of domains. Most of the swarms are related to relatively young features, and if normal faults are present, the swarms are most likely associated with them. Although fracturing probably occurred near surface, the controlling stresses were probably deep seated and the lineaments most likely result from brittle fracture. Where ground checked, most of the lineaments were found to be steeply-dipping zones of more intense jointing.

Wong, Teng-fong and Biegel, R. 1985. Effects of pressure on the micromechanics of faulting in San Marcos Gabbro. *Journal of Structural Geology*, vol. 7, pp. 737-749.

Keywords: gabbro, experimental work, microcracks

Griffith fracture theories assume macroscopic failure is due to extension of a single microcrack of proper size and orientation, but later microscopic work shows that the fracture process involves a multiplicity of microcracks. Coalescence often occurs in the post-failure phase and the process involves mechanisms dependent on mineralogy and grain size. The purpose of the paper is to look at the micromechanical processes using Scanning Electron Microscopy. Sample preparation is described. The cracks in the pre-failure samples are probably tensile, were mainly in plagioclase and biotite and result mainly from re-opening of pre-existing, healed cracks. Compared to post-failure samples, en echelon cracks are rare. A drastic increase in crack area occurs between 80-93% of peak stress. In the post-failure samples, the en echelon cracks have coalesced, cracks along grain boundaries have opened as have most of the healed cracks, and kinking is common, especially in biotite. These observations indicate a considerable, possibly previously unrecognized, influence on propagation is exerted by preexisting planes of weakness. The surface area/unit volume for healed/sealed cracks is very high. This distribution is relatively isotropic, which suggests a thermal, rather than tectonic, origin. The authors conclude that "...the stress-induced crack surface area increases whereas the stress-induced anisotropy decreases as a function of pressure" (p. 748). Also, microcracking in biotite plays a significant role in shear localization.